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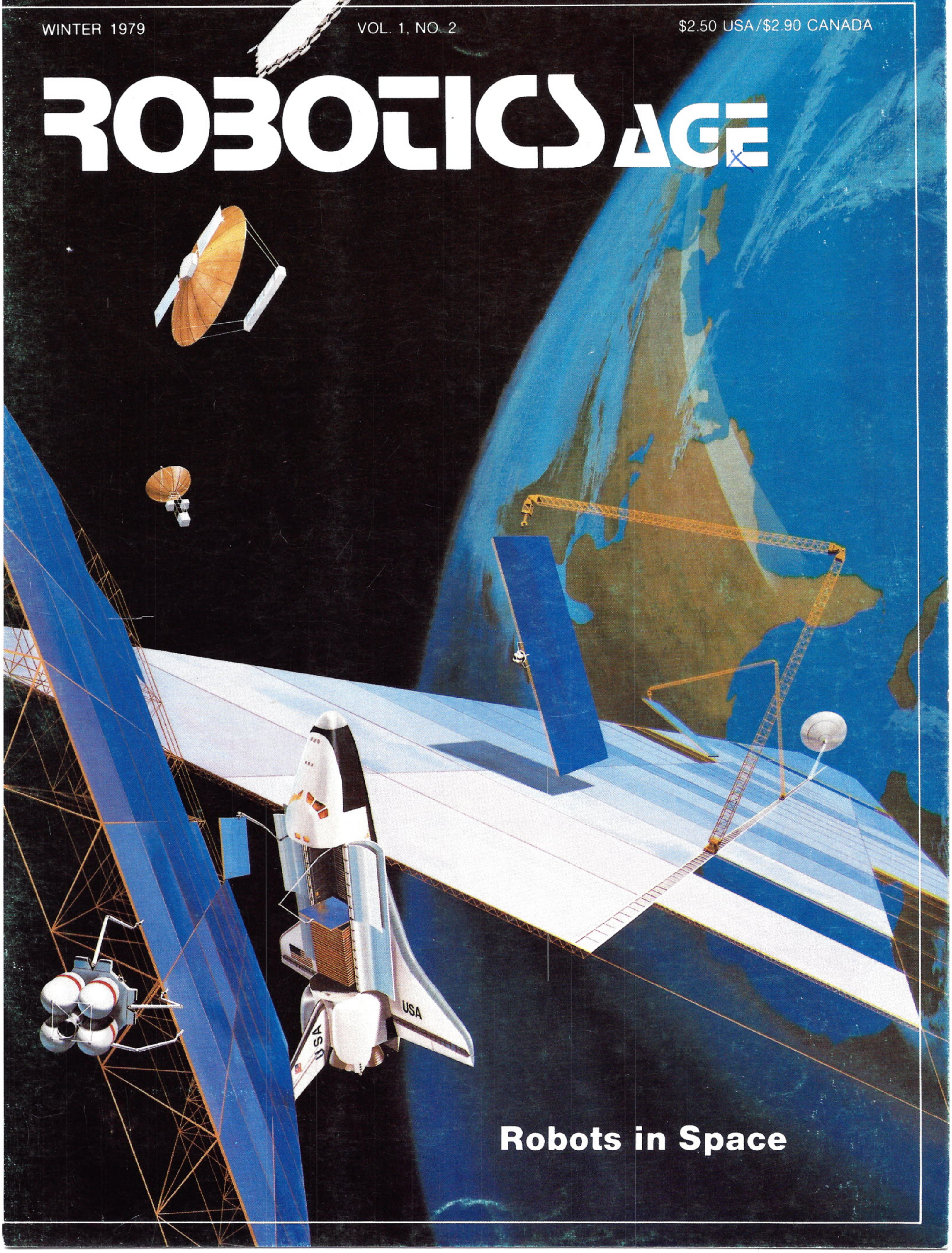
ROBOTICS AGE



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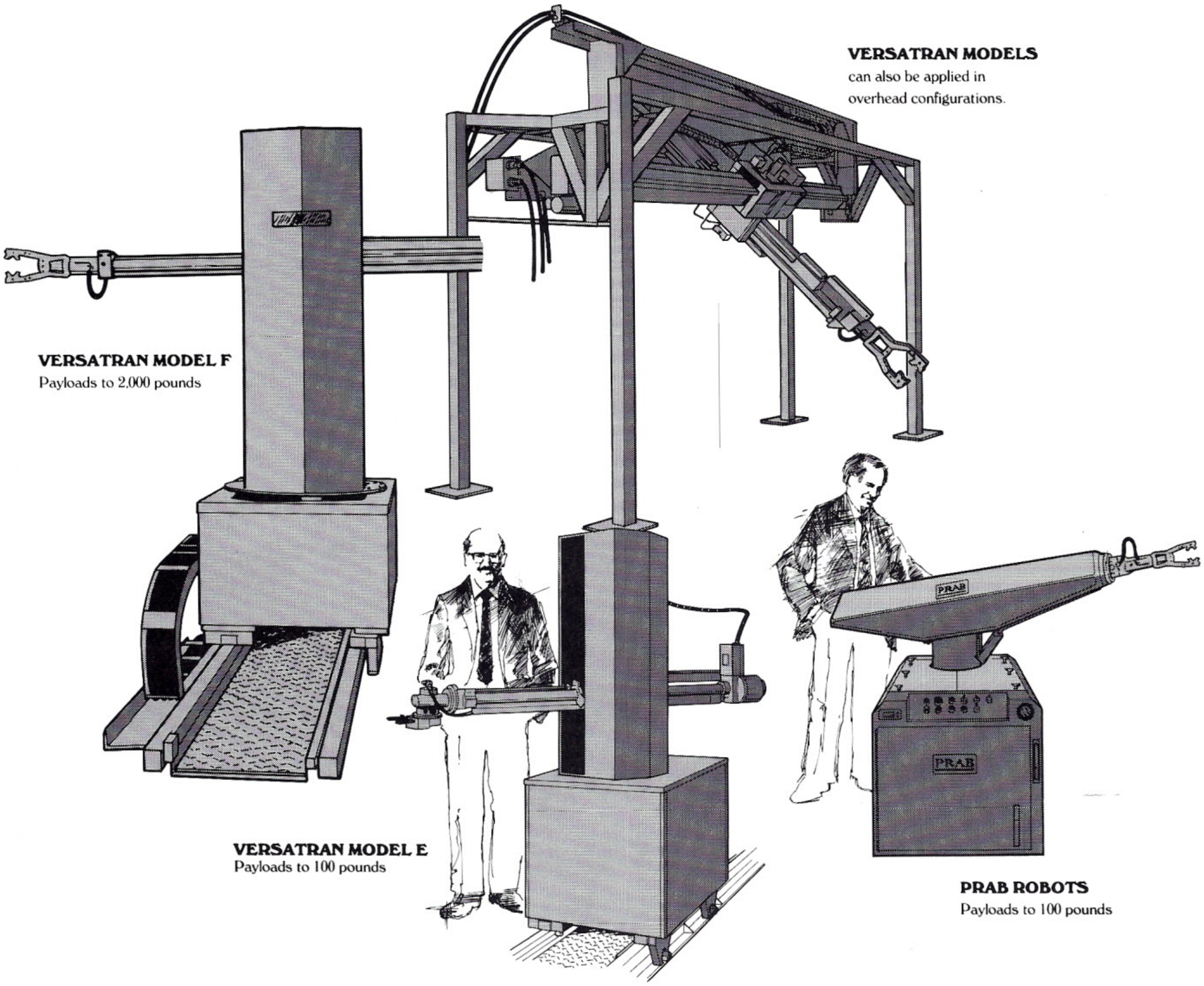

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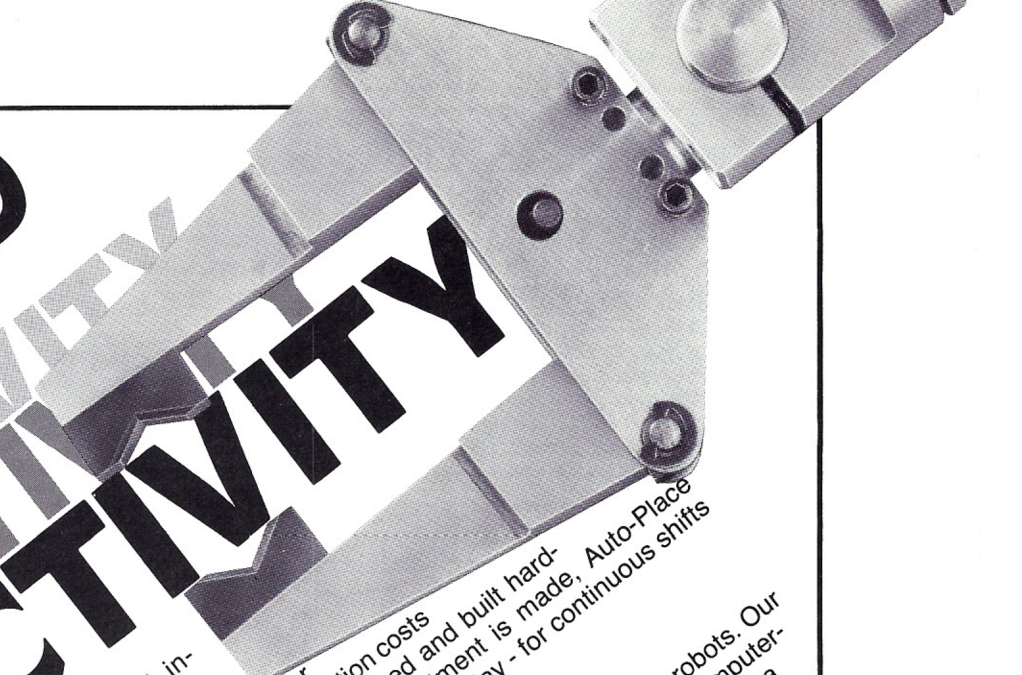

ROBOTICS AGE WINTER 1979 Vol. 1, No. 2

Articles

Departments

ROBOTICS AGE is published four times a year, in the summer, fall, winter, and spring by Robotics Publishing Corporation, 5147 Angeles Crest HWY, La Canada, CA 91011. Subscriptions are $8.50 for one year in the USA. Application to mail at Second-Class Postage Rates is pending at La Canada, CA. POSTMASTER: Send address changes to ROBOTICS AGE, P. O. Box 801, La Canada, CA 91011.

Subscriptions from Canada and Mexico are $10 for one year. Other foreign countries $15 for one year surface delivery. Single copy price is $2.50 in the US and $2.90 in Canada and Mexico, $4 in Europe, and $4.50 elsewhere. Foreign subscriptions and sales should be remitted in United States funds drawn on a U.S. bank.

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In this Issue . . .

Welcome to the second issue of ROBOTICS AGE. We are most pleased with the enthusiastic approval we've received from our many new subscribers, distributors, and advertisers. If you saw our first issue, you may have noticed it was designated the *Summer 1979* edition. Don't be alarmed—you haven't missed an issue. Our distributors encouraged us to bring the magazine out well in advance of the cover date so their displays would look current—we just called this the *Winter 1979* issue to comply with their wishes. Of course, subscribers will get the proper number of issues despite the change.

We are quite excited about the contents of this issue. While searching for new research results to report in the magazine, I learned from a colleague about a new design for a switched-mode power amplifier that offered better performance than most linear amps but with higher conversion efficiency than other switchers. Since I knew that the efficiency of conventional designs decreases with improved response, I investigated further. After reading several technical papers, I realized the vast potential of the Ćuk Converter for applications in robotics.

When I found out the discovery was made at Caltech, which is practically next door to me, I contacted Professor Ćuk about presenting the new invention to our readers. I wanted the article to assume only the most basic background in electronics, but this turned out to be no problem, due to the authors' exceedingly lucid explanations. The result is a series of articles, beginning in this issue, about this truly revolutionary innovation in power circuit design. The series, as you will see from the theoretical discussion herein and from the working circuits and applications to be described in Part II, will give you all you need to apply this breakthrough to your own robot designs.

Our cover story, "Robots in Space", gives us a clear understanding of the vital role that advanced robot and automation technology will play in the future utilization of the vast resources of space. The early application of robotics and machine intelligence techniques will greatly hasten the economic feasibility, and thus the practical realization, of these exciting ventures.

While in Tokyo to present a research paper at IJCAI6, I had the privilege of meeting two of Japan's energetic and creative team of robotics researchers. Drs. Kunikatsu Takase and Tokuji Okada, of the Electrotechnical Lab in Tokyo, both presented films at IJCAI of the almost unnervingly human-like behavior of their research robots. They both kindly assisted us in preparing adaptations of their technical papers for our readers. We hope you find them enjoyable as well as informative. Our intent is to provide a brief description of the robots and the innovations they embody, together with a set of references that will allow you to pursue the complete technical details if you desire.

Finally, my friend Keith Price, of USC's computer vision group, helped me put together an overview of the IJCAI Conference and the topics covered there. Perhaps it was a little overambitious to attempt to condense the entire spectrum of current AI research into a few pages, but if any particular area stimulates your interest enough to learn more about it, we will have succeeded in our real goal. Besides, you can always order the proceedings if you want more detail—they would love to sell you a copy.

Readers of our first issue may be disappointed about the absence of two features that were promised for No. 2, namely the Robotics Product Index and further details on the ROBOTICS AGE Competitive Event (RACE). The Robotics Product Index is missing because we simply were not able to compile all of the information needed in time for this issue. As for publishing the rules for the RACE, we decided to delay these details due to interesting developments closely related to the contest. In seeking sponsors for the competition, we found one who may be willing to go all the way!

Instead of—or in addition to—providing prize money for the various categories of the RACE, this private foundation expressed an interest in offering a *substantial* cash prize (comparable to the famous *Kremer Prize* for man-powered flight) for the development of a successful household robot. Although the arrangements were not final by presstime, we hope to combine this prize competition with the RACE, hence the delay. Expect more news in the next issue.

Again I want to express my special thanks for your overwhelmingly favorable response to ROBOTICS AGE. Circulation has been growing beyond our most optimistic expectations. We sincerely apologize for the empty shelves of the many distributors who sold out early (some within two days of receiving their consignment). We have had to more than double our original press run to attempt to satisfy your demand for Robotics Age, and we pledge ourselves to continue giving you the quality content that has made it successful.

—Alan Thompson

LETTERS

Editor, Robotics Age:

I propose a category of "show robots." After reading the first issue of the very excellent Robotics Age Magazine, I was left with the impression that the editor and publisher considered this category slightly frivolous, especially if one utilized only radio-controlled devices. I have been involved for several years in developing show robots and producing many shows for commercial accounts and fairs. This experience should qualify me to communicate my proposal and helpful advice to your readers. Furthermore, I am perhaps the only one in the nation who has worked closely with a wide range of fellow show robot builders.

Each of us, as humans, has our strengths, weaknesses, and idiosyncrasies, which, I also suspect, is what helps produce full-time robot builders in the 70s. I began as an agent for Quasar Industries at a time when they were just launching their publicity campaign and claim to a "domestic android." I quickly became skeptical and had many heated coast-to-coast telephone calls with Quasar's president, Tony Reichelt, especially regarding his tactics with the press. At that time, I made the decision to split from Reichelt's organization—a time when it appeared as though the Domestic Android could be a multi-million-dollar bonanza.

Although I differ greatly with Reichelt on many subjects and approaches to business, in the following two years that I have undertaken a full-time business of building show robots and renting them to industry and fairs, I have learned some respect for him. Anyone who has been operating show robots for ten years or more probably deserves special recognition, regardless of the degree of controversy surrounding them. Surviving the prototyping of a product, obtaining paying accounts, and late payment for services from some of America's largest corporations, along with personnel problems, is slightly more difficult than commuting to a 9-to-5 job and criticizing show robots over a cup of coffee in the lunch room.

Prototyping even the most rudimentary, radio-controlled "robot" that will run reliably for 6-8 hours on any given show day is a gruelling task. My primary message to Robotics Age readers is: nothing is truly simple, and achieving simplicity of design and construction is perhaps the greatest achievement in any industry. Whereas my own education was non-technical, I have found in 10 years of experience in the amusement game industry, and now several years in dealing with show robots, that engineers tend to get overly technical and put a greater emphasis on drawings than on how a person is going to service a robot quickly in some remote town under the pressures of a corporate client paying a rental rate of $500 a day or even more than $1,000 a day.

My second message is to be wary of criticizing the radio-controlled method of show robots until you have built one yourself, or, I might even add, a *better* one. Android Amusement Corp. deals with press and clients in a very straightforward manner—even helping to educate the media about what constitutes a real robot, versus our type of radio-controlled show robot, and the limitations.

I commend Robotics Age on providing a forum for robot people and the contest to promote developments. I'm just hoping that some of the contest entrants will keep some of our criteria in mind—in particular: portability, airfreight shipping requirements, and ease of operation even by non-technical personnel. We welcome all interesting and exciting developments—if someone can produce a more practical method of robot control for shows, great! However, I personally think that Robotics Age ought to retract their restriction and invite entries under a show robot category.

Gene Beley, President
Android Amusement Corp.
Arcadia, California

Editor's reply:

We welcome this opportunity to correct any misunderstandings that may have arisen from the editorial published in our first issue. Our comments were directed against those who have intentionally deceived the public about the capabilities of their "robots" by obscuring the fact that the machines are remote-controlled by humans. The editorial was not by any means intended as a blanket indictment of "show robots." Obviously there is a demand for teleoperated robots, especially those with a humanoid appearance, in many areas of the entertainment industry. Some of our favorite sci-fi movies have been immeasurably enriched by the roles played by "show robots," and of course, deception is an important element of acting—no one likes cheap special effects that are too obviously staged.

Nor do we consider the development of teleoperated equipment a frivolous pursuit—neither the nuclear industry nor, as described in this issue's cover story, the future industrialization of space would be possible without such devices. As

(continued page 59)

Prof. Slobodan Ćuk
and
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California Institute of Technology
Pasadena, CA 91125

Advances in SWITCHED-MODE Power Conversion

ROBOTICS AGE is honored to present a significant innovation in solid-state power conversion, described here by the inventors themselves. The new design is certain to have a profound impact on the electronics industry, but, because of its generality and many potential applications in robotics, we wish to familiarize our readers with its design and operation.

Rather than just summarizing the advantages of the new design and suggesting possible applications, we decided to present a thorough discussion of the background, development, and operation of the Ćuk converter, so that even readers unfamiliar with the former state of the art in switching converter design can more fully appreciate the significance of the invention as well as understanding the principles behind it. What emerges is a fascinating account of the process of invention, expressed in the scientists' own words.

Introduction

Switching power supplies and regulators ("switchers") have come into widespread use in the last decade. Because of their much higher efficiency, smaller size and weight and relatively low cost, they are displacing conventional linear power supplies even at low power levels (about 25 Watts). The design of switching converters has been extensively studied, and it is commonly believed that the designs in commercial use today employ the simplest possible switching structures for dc-to-dc level conversion.

However, even though high conversion efficiency has been achieved, present switching converter designs posses several undesirable characteristics. Rapid switching of the input or output currents can cause severe electromagnetic interference (EMI) problems, requiring the addition of appropriate filters that increase both the complexity and cost of the circuit. Also, the implementation of the power

transistor switch requires complex drive circuitry in configurations where the emitter voltage "floats" above ground. In switched-mode power amplifier designs, additional problems are imposed by the requirements for dual (bipolar) power supplies, high switching frequencies, and complex feedback circuitry.

A revised look at present converter designs and an analysis of switching circuit topology has led to the discovery of a new design that retains all the desirable properties of conventional designs, with none of their undesirable attributes. Both input and output currents are essentially nonpulsating dc, and, in fact, ripple can be reduced to zero. Furthermore, the new topology may be implemented with fewer parts than comparable solutions, and thus may be said to be an "optimal" design.

Because of its simplicity and generality, the new converter can efficiently raise or lower dc levels, and, with minor modification, bidirectional power flow can be easily achieved, allowing the roles of power source and load to be arbitrarily interchanged without physically switching their connections. A switching power amplifier based on the new converter requires only a single power supply, enabling efficient dc to ac power conversion. The improved performance of the new switching power amplifier design permits the use of a lower switching frequency and simple circuits for both the drive and feedback.

We will begin with a discussion of switching converter design, leading to the development of the new converter. Next, the design of a switched-mode power amplifier using the new converter and a discussion of its performance will be presented.

A Review of Switching Converter Design

In the basic design of the linear power supply, shown in

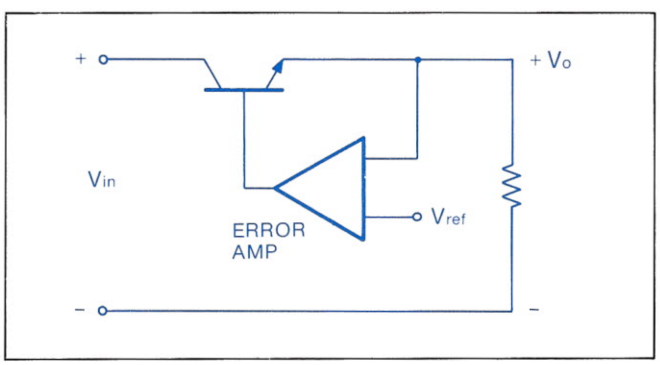

Figure 1. Conventional linear power conversion.

Figure 1, the output voltage, V_o, is regulated to a multiple of the reference voltage, V_{ref}. The difference between the unregulated input voltage and V_o results in power dissipation in the transistor, which, in high current supplies, can result in considerable energy loss and heating. Consequently, the unregulated voltage must be kept as low as possible while still allowing adequate regulation.

Switching power supplies are based on the principle that, by alternately switching the transistor completely off and on, its power dissipation can be held to a minimum. Passive energy storage elements, inductors and capacitors, can then be used to transfer energy from the source to the load, performing the appropriate level conversion in the process.*

Figure 2 shows the most commonly used switching configuration, referred to as the "buck" converter. The ideal switch, S, can be realized by the combination of a bipolar transistor and commutating diode as shown. In operation, the input voltage is connected by S to charge inductor L to the output current necessary to produce the desired voltage, V, across load R. Once V is attained, S disconnects the input and provides an alternate path for the inductor current, which then begins to decay. The output capacitor, C, helps reduce the residual voltage ripple caused by the switching. The cycle repeats at a fixed rate, and the average voltage gain is equal to the duty ratio, D (the fraction of the switching cycle that the transistor is on).

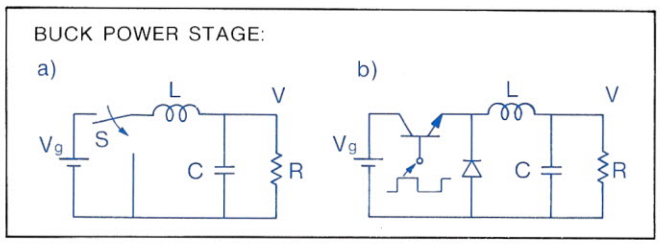

Figure 2. The basic "buck"-type switching converter configuration, showing (a) the topology of the circuit, using an idealized switch, S, and (b) the implementation of the switch using a bipolar transistor and a commutating diode.

* Recall from basic physics that energy is stored by an inductor in the magnetic field produced by the current through its winding. A voltage applied across it either increases or decreases this current to energize or deenergize the field. Conversely, the current through a capacitor either charges or discharges the energy stored in an electric field, respectively raising or lowering the voltage across its terminals.

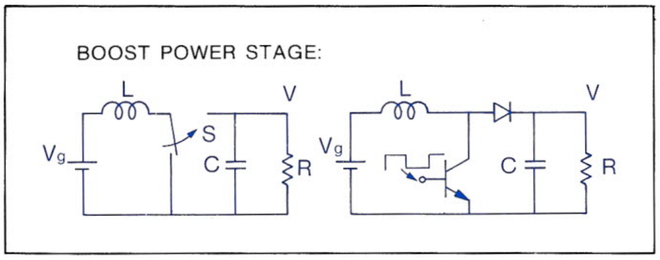

Figure 3. The common "boost" converter configuration: (a) circuit topology, using an ideal switch, and (b) implementation.

Note that the input current to the regulator alternates between the full output current and zero. This abrupt variation in the input energy flow causes severe EMI, and invariably requires the presence of an input filter to smooth out the substantial current ripple component at the switching frequency. Also, since the emitter floats above ground, isolated drive circuitry (not shown) is required to switch the transistor. A further limitation of this design is that only voltage reduction is possible, since D is less than 1.

For applications requiring a voltage step-up, some of the drawbacks of the buck configuration can be avoided by using the "boost" converter configuration, shown in Figure 3. In this design the inductor is always in series with the input, so that the supply current is continuous. The inductor stores energy when grounded by S, and then the stored energy is released to the output. The output voltage of the boost converter is always greater than the supply, with an ideal gain equal to $1/(1-D)$. Note also that the grounded emitter of the transistor switch simplifies the drive circuit. The drawback of the configuration, however, is that during the inductor charging interval, all the output current must be supplied by discharging the output capacitor, resulting in considerable output ripple.

I. Development of the New Converter Topology

The discovery of the new converter design resulted from the objective of retaining the desirable properties of both types of converters. This goal was realized by examining combinations of the two basic types, with the underlying principles of simplification and optimum interconnection while simultaneously maximizing performance. The details of the analytical technique, described more completely in [1], will be abbreviated here.

Consider the cascade connection of a boost power stage followed by a buck power stage, resulting in the converter shown in Figure 4. This configuration retains the desirable properties of the low input current ripple of the boost converter and the low output current ripple of the buck stage. The voltage gain of the converter is the product of the gains of the two stages. Assuming that S_1 and S_2 are synchronized so that both switch from position 1 to 2 (and back) simultaneously, the resulting ideal gain is D/D', where $D'=1-D$. Thus, the same converter can be used for both level reduction ($D < .5$) and increase ($D > .5$).

The undesirable output ripple of the boost converter is now isolated between the stages, and, in fact, the capacitor serves as the sole energy transfer mechanism between the stages. To see this, note that during the part of the cycle when both switches are in position 2, C_1 is isolated from the output circuit and is charged by the input current through L_1. In the rest of the cycle, C_1 is completely transferred to the output circuit and is discharged by the output current through L_2, reenergizing L_2 while L_1 stores energy from the input. Position 2 of S_2 provides a path to sustain the output current (from energy in L_2) while C_1 is being recharged by L_1.

The issue remains, however, as to whether or not this design represents the optimal configuration of this attractive boost-buck cascade. It is apparent that the two inductors are essential to the continuity of the input and output currents, and that the intermediate capacitor is required for energy transfer. The issue of optimality thus resolves to the following question:

Can the number of switches in this cascade configuration be reduced from two to one and still achieve capacitive energy transfer?

The answer to this question may at first seem surprising. Switches S_1 and S_2 may indeed be combined, resulting in a new optimal converter configuration. The solution is found by considering the topological properties of known converter types and their cascaded combinations. [1, 2] A key to the solution is that inversion of the converter's output voltage is a necessary feature of the new design. Since both of the basic converter types are noninverting, the

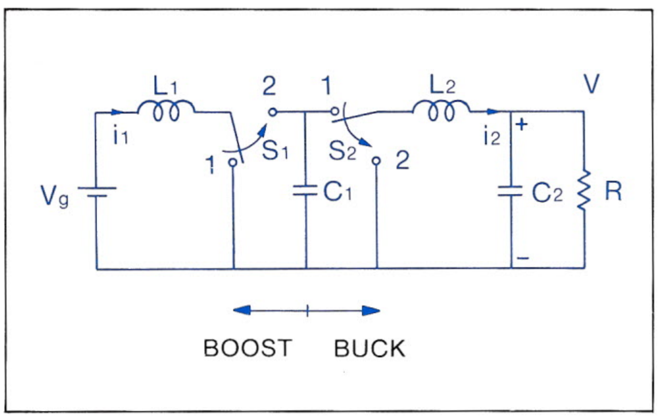

Figure 4. Cascade combination of a boost and a buck power stage.

"Even though a true dc-to-dc transformer is physically impossible, the new converter can functionally be considered as such . . . "

only way to achieve this is by reversing the polarity of the charged energy transfer capacitor when it is switched into the output circuit. Attention to this issue alone leads to the solution shown in Figure 5.

Even though a true dc-to-dc transformer is physically impossible, the new converter can *functionally* be considered as such, since both its input and output voltages *and currents* are very close to true dc quantities, owing to the negligible switching ripple. Moreover, due to the advantages of capacitive energy transfer, the actual conversion efficiency of the new circuit is substantially greater than that of conventional designs. [1] The grounded emitter of the switching transistor also allows the most simple drive circuitry to be used.

In this design, the single switch S alternately grounds the opposite ends of the capacitor, effectively switching it from the input to the output circuits. C_1 is charged by the input current to a positive voltage, as viewed from left to right, with S in position B. With S switched to A (during the charging interval of L_1) the "positive" side of C_1 is now connected to ground, and its "negative" side (since the voltage across it does not change) effectively "pulls down" the voltage level at terminal B. Thus, current flows *from* the grounded load to discharge C_1 through L_2, causing a negative voltage drop across the load, hence a negative output voltage.

The hardware implementation of the new converter, using a transistor/diode combination to implement the ideal switch S as in the other converter configurations, is shown in Figure 6. With the transistor off (open), C_1 is charged by the input current through the forward biased diode. When the transistor turns on, it provides a charging path for L_1, but also drops the positive terminal of C_1 to (very near) ground. As in the ideal case, this pulls down the output voltage, reversing the bias on the diode (turning it off) and transferring the stored energy to L_2 in the form of increased current. Note that the dual role of switch S, its inclusion in the input and output circuits simultaneously, requires that the transistor and the diode, when conducting, must carry both the input and the output currents.

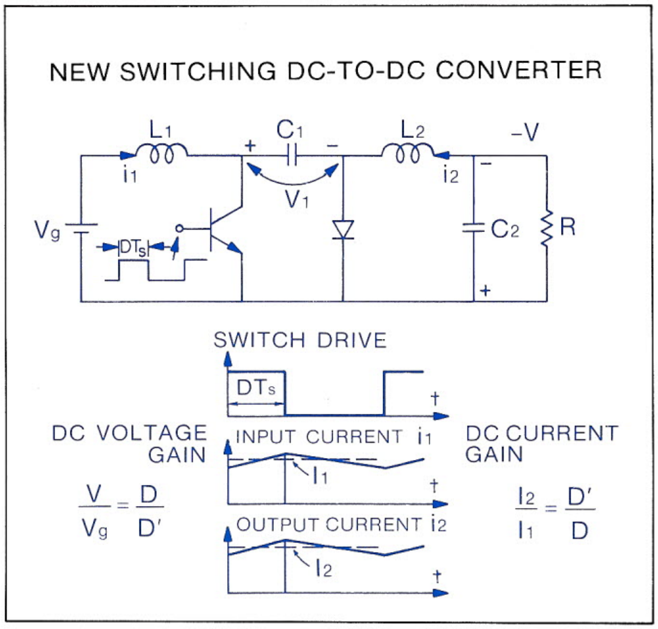

Figure 6. Hardware realization of the Ćuk converter using a transistor and a diode to implement switch S. Ideal dc voltage and current gains are as shown.

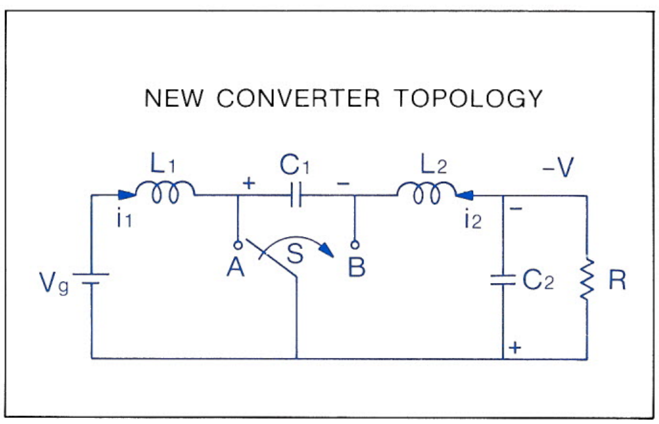

Figure 5. The new switching topology, employing capacitive energy transfer with polarity inversion of the output voltage.

Coupled Inductor Extension of the New Converter

It would seem from the above discussion that the simplest possible converter circuit has been obtained, but this is not the case. Consideration of the voltage waveforms across the two inductors L_1 and L_2 over the switching cycle reveals that, for the average dc voltage across each inductor to be zero, (steady state balance condition) the two waveforms must be identical. [3] This means that the two inductors may be coupled by being wound on the same core, without affecting the basic dc conversion property, provided that the resulting transformer has a 1:1 primary to secondary voltage ratio. This is easily achieved by setting L_1=L_2, (same number of turns in

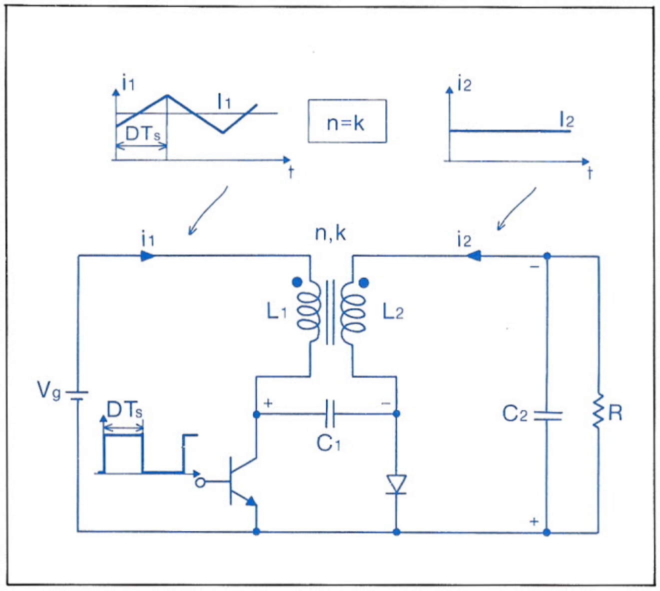

Figure 7. The Coupled Inductor Extension of the Ćuk converter. With appropriate transformer design, the output current ripple can be reduced to zero.

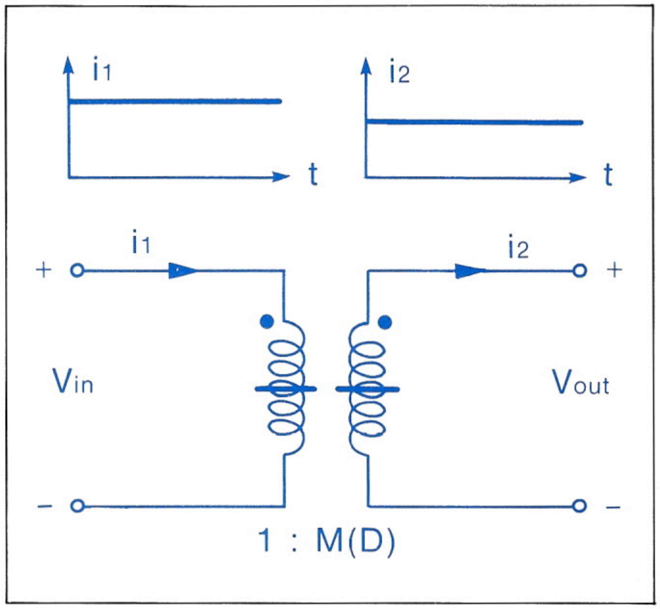

Figure 8. The ultimate objective of switching conversion — a dc-to-dc transformer with constant input and output currents and an electronically controllable effective turns ratio for voltage level change.

each) with the direction of coupling as shown in Figure 7.

The resulting circuit not only eliminates one inductor core, (for further component savings) but has an interesting property that profoundly affects the performance of the new converter. Since the coupled inductors form a transformer, inductive energy transfer between the two windings alters the effective inductance of each. For a 1:1 turns ratio, both inductances are approximately doubled, so that both input and output current ripples are about one half those of the uncoupled converter. Even more significant, however, is that by slightly altering the turns ratio, one of the effective inductance values can be made arbitrarily large, dramatically reducing the current ripple on that side. When the effective turns ratio (primary to secondary) matches the inductive coupling coefficient of the transformer*, the output current ripple can be completely eliminated, resulting in pure dc to the load. [3] In this matching condition, no output capacitor is needed, since the load voltage is also constant.

The coupled-inductor converter thus has the simplest possible structure, consisting of a single transformer, commutation capacitor, and a single switch (realized by two semiconductors), and yet it achieves the maximum performance (both input and output current nonpulsating with one of them even being pure dc with no ripple) in a topology which offers the smallest possible size and weight and highest efficiency.

It is interesting to note that the idea of coupling the inductors is a new concept which can be implemented with similar benefits to many other switching converter configurations. Nevertheless, the greatest potential of this configuration is obtained through its application to the new converter topology, on which it was originally conceived.

Yet, this still seems to fall short of the ultimate objective, the functional realization of the ideal dc-to-dc transformer shown schematically in Figure 8, which has constant current at *both* input and output. In addition, the dc isolation between input and output shown in Figure 8, often required in many practical applications, is not present in any of the converter extensions discussed so far. This, however, poses no insurmountable problems, since there is an elegant way of introducing dc isolation into the new converter by the addition of a single ac transformer and an extra capacitor, as described in detail in [4]. Furthermore, the same idea of coupling inductors in this dc isolated extension leads also to zero current ripple on one side.

The latest generalization of the new coupled-inductor converter concept has resulted in what may be considered the ultimate solution: a dc-isolated switching dc-to-dc converter with zero current ripple at BOTH input and output terminals, which functionally emulates the ideal dc-to-dc transformer of Figure 8†.

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* Like the effective turns ratio, the inductive coupling coefficient is a physical property of the transformer construction, with a value ranging from 0 (separate inductors) to very near 1 (windings closely wound on a single ferromagnetic core).

† Technical details of this latest development have not yet been publicly released, but are contained in a patent application. The basic Ćuk converter configuration and many of its improvements, as well as new switching power amplifier configurations, are protected by a series of patents. [9, 10, 11, 12]

A General and Unified Approach to Power Converter Topology

Modular Concept

A large number of switching configurations are currently available for a multitude of power conversion functions. Heretofore, some circuit configurations have been solely used to perform the dc-to-dc conversion function (converters), others for dc-to-ac conversion (inverters), and yet another for power amplification, with their circuit configurations having nothing or very little in common. With the family of Ćuk converters, however, a vertical integration has been made, and for the first time a logical extension from a single-quadrant to a two-quadrant converter (battery charger/discharger) and finally to a four-quadrant converter (bidirectional power amplifier) has been realized.

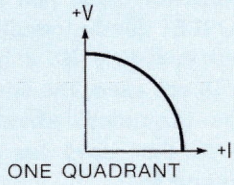
Quadrant Classification

Power Processing Systems may be classified according to the nature of their output capabilities. The simplest is a dc-to-dc converter in which output current is delivered in one direction at one output voltage polarity. This means that on a graph of output voltage V versus output current I, only ONE QUADRANT is available, as shown for positive V and I in Figure A. This is structurally the simplest switched-mode converter, and can be realized with only one transistor and one diode, as in the Ćuk converter illustrated.

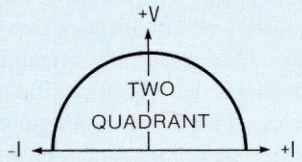
Simply by doubling the number of power devices in the Ćuk converter of Figure A, the output capability of a dc-to-dc converter can be extended so that current can flow in either direction (bidirectional current switch implementaiton), and the system becomes a TWO-QUADRANT converter as shown in Figure B. Thus, INPUT and OUTPUT can be arbitrarily interchanged, and the converter is capable of BIDIRECTIONAL POWER FLOW.

Finally, by the new general concept of converter topological interconnection illustrated in Figure 21, a two-quadrant converter is extended into a FOUR-QUADRANT converter in which the directions of both voltage and current can change independently as shown in Figure C. Hence, a true AC OUTPUT can be obtained together with bidirectional power flow.

Although this vertical integration has been conceived for the family of Ćuk converters, it can be directly applied to other converter types, such as buck, boost, or any other switching configuration.



(A)



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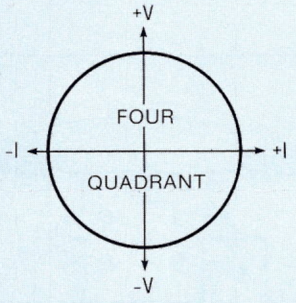
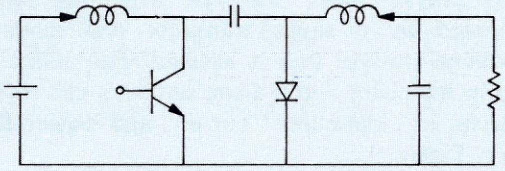
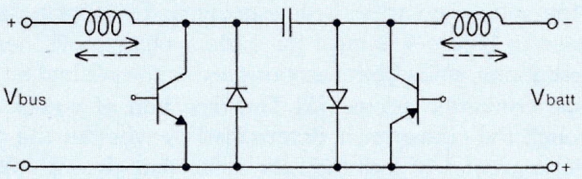


(C)

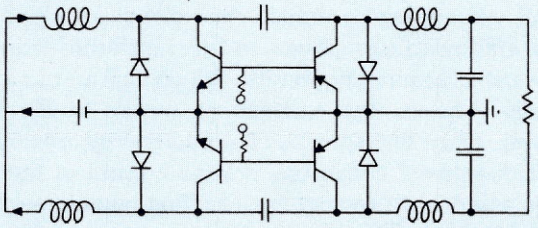
Basic Ćuk Converter



Battery Charger/Discharger



Bidirectional Power Amplifier



Applications

The Ćuk converters have a broad range of applications in all aspects of power processing. Robotics, in particular, will benefit from the excellent performance of Ćuk converters in motor control. Its high efficiency and low noise make it an obvious choice as a dc motor servo drive, with regenerative braking, in either the two- or four-quadrant configurations. In fact, the high performance of the Ćuk bipolar amplifier make it possible to design servo systems employing ac induction motors, capable of optimum motor drive as well as regenerative braking.

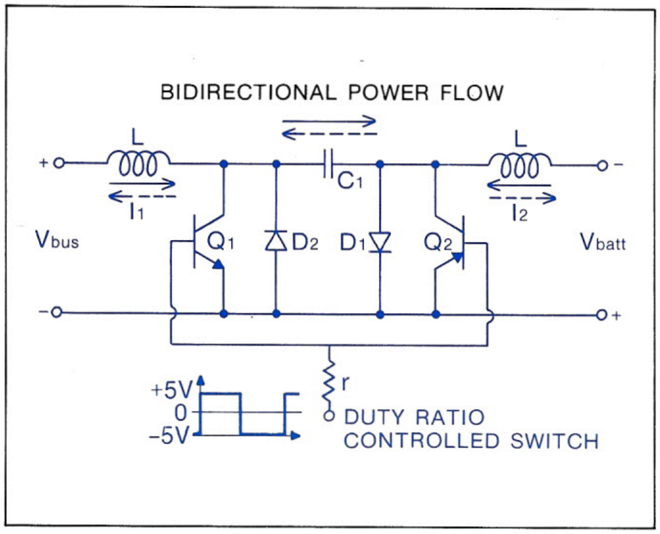


Figure 9. A symmetrical implementation of the Ćuk converter, capable of power transfer in either direction.

Bidirectional Power Flow in the New Converter

Note that the configuration of the new converter shown in Figure 5 is completely symmetrical with respect to the designation of the input and output terminals. Because the ideal switch S allows current flow in either direction, either terminal of the converter can behave as a current source or as a current sink. However, when the switch is implemented by a single transistor and diode, only unidirectional current flow is allowed. The addition of a single pnp transistor and a diode removes this constraint and results in bidirectional current and power flow as shown in Figure 9.

The converter circuit is thus symmetrical, and the input and output terminals can be arbitrarily designated (as long as the voltage polarities are respected). The configuration shown in Figure 9 is ideal for battery charger/discharger applications, since both functions are accomplished by this single converter circuit. [5] The direction of power flow through the converter is determined by whether the duty ratio is greater or less than the value that gives a voltage gain equal to the ratio of the bus to battery voltages. In general, attempting to reduce the voltage to a load that stores energy causes power to be transferred from the load,* just as attempting to raise the voltage across a load normally requires the transfer of power to the load. However, when two sources of stored energy are coupled by a bidirectional converter, precise control of the duty ratio is essential to restrict the resulting power flow to an acceptable limit. The bidirectional current switch implementation is equally applicable to the coupled-inductor extension (Figure 7) of the new converter.

**Editor's note: A very useful application of this is to use a dc drive motor as a generator for regenerative braking, recovering some of the energy stored in a robot's momentum or provided by an external source (as when rolling down a slope).*

Since both of the transistors in Figure 9 are referenced to ground, the complementary switching of the pair can be accomplished by a single drive source as shown. Moreover, because the two base junctions are tied together, the circuit also automatically prevents the simultaneous turn-on of both transistors, (and thus prevents shorting out capacitor C) in spite of the presence of transistor switch storage time.

Another implementation of the bidirectional current switch is made possible by recent technological advances in Metal Oxide Semiconductor Field Effect Transistors (MOSFETs). Formerly limited mostly to small signal applications, newer MOSFET devices are capable of switching to a relatively low ON resistances, with a substantially higher current rating. It is not widely known that the power MOSFETs are capable of bidirectional current flow. Owing to the device's internal construction, there is effectively an inherent diode connected betweeen drain and source which provides the alternate (opposing) current path. Hence, each transistor/diode pair can be replaced by a single power MOSFET device, resulting in the bidirectional converter shown in Figure 10. If both p-channel and n-channel MOSFETs are used, the source terminals of both devices may be grounded, allowing a simple driving scheme similar to that used for the grounded-emitter transistors in Figure 9.

Besides reducing the component count, power MOSFETs have a number of advantages over bipolar transistors which make them especially attractive for switching converter applications. [6] Whereas bipolars are current-controlled devices, FET's are voltage controlled. As a consequence, they require much lower drive currents and are capable of very fast switching speeds. Also, unlike

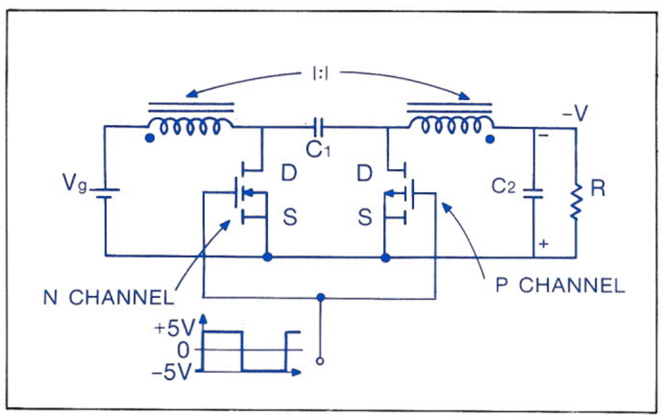


Figure 10. Bidirectional switching converter using MOSFET power switches.

bipolars, several MOSFETs can be easily paralleled to distribute switching current. Their switching speed (5ns typical) is one or two orders of magnitude faster than comparable bipolars, (200ns typical) significantly reducing power loss during switching. Although older power MOSFETs had a high saturation voltage compared to bipolars, (3V@ 10A vs. 2V or less for a bipolar) the newest devices have as little as 0.055 ohms R_{SD}, making their use in converter designs extremely attractive, especially for applications requiring a high switching frequency.

II. Application of the New Converter Circuit to Switched-Mode Power Amplifier Design

Although a substantial effort has been made in recent years toward the development of complex switching power supplies, substantially less attention has been devoted to their natural outgrowth — switching power amplifiers. It is quite natural, then, that the principles of the operation of switching amplifiers are not widely known. We will begin, therefore, with a review of present designs, which are all based on a modification of the "buck" power stage of Figure 2. This review reveals substantial performance deficiencies originating from the buck converter itself.

The new circuit topology of Figure 5 eliminates most of the problems associated with earlier switching converter designs, providing greatly improved performance with fewer components. This, together with the extension of the new design to allow bidirectional current flow, suggests that the design of switching amplifiers should be reexamined in light of this new development. Indeed, we will show that a power amplifier design based on the new converter topology provides a much superior solution.

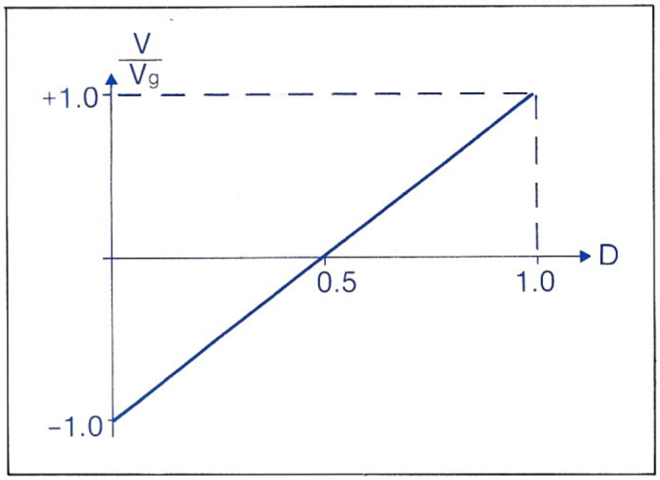


Figure 12. DC voltage gain of the power stage in Figure 11.

Switching Amplifier Principles of Operation

The major difference between the power stages of a switching amplifier and a switching power supply is that the former must be capable of producing an output of either polarity. In all present designs, this is accomplished by modifying the basic buck power stage to use two power supplies $+V_g$ and $-V_g$ as input, with the switch S switching between positive and negative supplies as shown in Figure 11.

The resulting voltage gain, shown in Figure 12, is a linear function of the duty ratio, D. For D greater than 0.5 the output voltage is positive, while for D less than 0.5 it is negative. Note that since the load voltage may be negative as well as positive, the implementation of switch S shown in Figure 2 is inadequate. Since the output voltage is determined by the inductor current, the hardware implementation of the switch must permit bidirectional current flow, as shown by the arrows in Figure 11. This is readily accomplished by the two-transistor, two-diode circuit shown in Figure 13. This bidirectional implementation is similar to that required for the symmetrical converter in Figure 9, but with the significant difference that neither transistor is referenced to ground, necessitating the use of isolated drive circuitry to accomplish the complementary switching action.

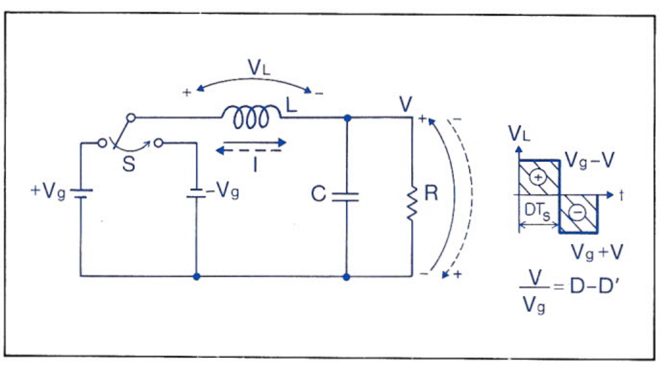


Figure 11. Modified buck power stage with output voltage of either polarity.

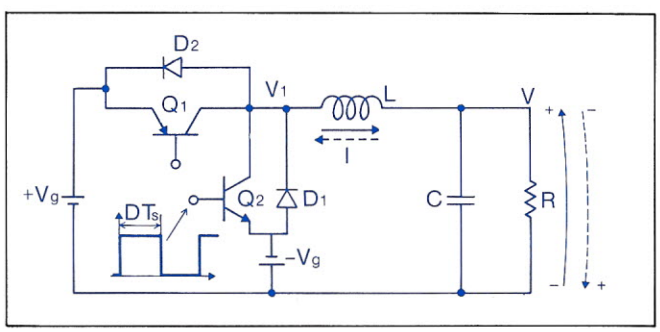


Figure 13. Practical implementation of the converter in Figure 11.

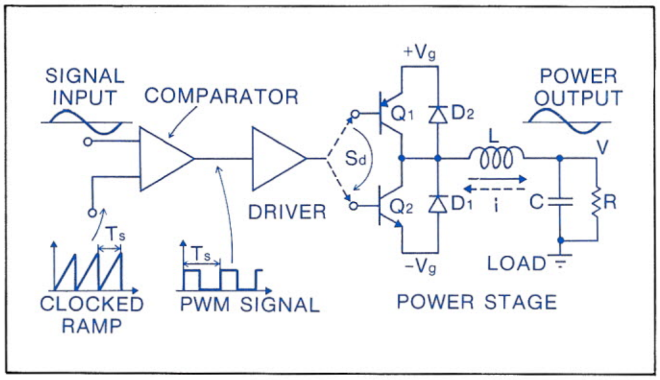


Figure 14. Open-loop buck type switching power amplifier.

To apply this dual-polarity power stage in a switching power amplifier, it is necessary to control the duty cycle so that the output voltage varies in proportion to the input signal. The linear voltage gain of the buck power stage facilitates this function, and is incorporated into the open-loop amplifier configuration shown in Figure 14. The design is the same as that for an open-loop dc-to-dc converter operated at a constant switching frequency $f_s=1/T_s$, with the only difference that a time varying (sinusoidal, for instance) input signal is used at the comparator input instead of a dc reference voltage. When the input signal is positive, a pulse with D greater than 0.5 is generated, producing positive output, while for negative input, D is less than 0.5 and negative output is produced. In fact, comparison of the low frequency input signal and the high frequency sawtooth (clocked ramp), generates a Pulse Width Modulated (PWM) signal, whose low frequency spectrum is, in effect, recovered by low-pass filtering with the inductor. Hence, a close replica of the input signal is generated at the output, but at a high power level.

The comparison of this switching amplifier approach with conventional linear designs with respect to the two foremost constraints in power amplifier design, efficiency and distortion, now becomes apparent. In terms of efficiency, this approach boasts the usual advantages of switching power supplies over linear — significantly lower power dissipation. Namely, its theoretical 100% efficiency is usually only slightly degraded (often it is over 90%) by losses due to nonzero transistor saturation voltage and switching time and parasitic resistances of storage elements in the power path.

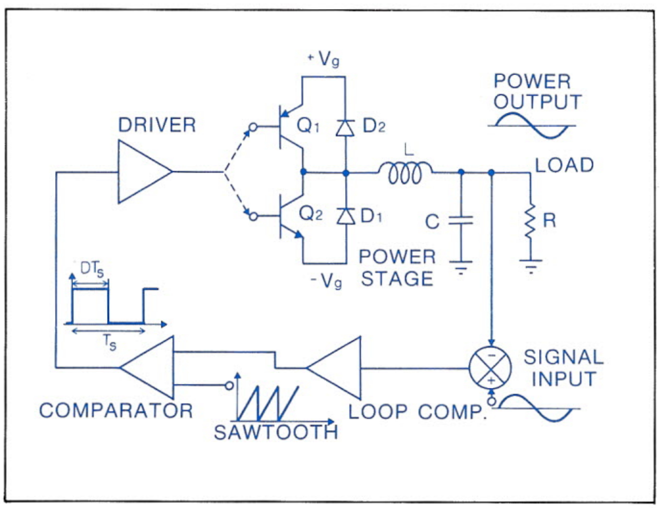


Figure 15. Closed-loop buck type switching power amplifier.

Distortion, however, becomes a function of the switching frequency, rather than being dependent on the linearity of the transistor gain curve. Specifically, for low distortion the switching frequency has to be an order of magnitude or so higher than the signal frequency to avoid overlapping sidebands in the PWM signal and to minimize the effects of output ripple. On the other hand, with increased switching frequency the switching time of the transistor may represent a significant portion of the duty cycle, introducing further distortion and degrading efficiency as well. Other distortion sources arise from nonlinearities in the clocked ramp (which also increases with switching frequency) and variations in the power supply voltages.

To reduce the effects of these sources of distortion requires the use of negative feedback, as shown in the block diagram in Figure 15. Feedback allows a reduced switching frequency and improves linearity at the expense of increased circuit complexity, but the amplifier in Figure 15 still has drawbacks that originate directly from the use of the buck power stage. As in the buck power supply design, the input currents pulsate, at the switching frequency, between zero and the output current, causing severe EMI. The design requires two power supplies of opposite polarity, and complex drive circuitry is required for the transistors, both to translate drive signals to the ungrounded emitters and to prevent simultaneous turn on of the transistors and shorting of the power supplies. Finally, a relatively high switching frequency (300 kHz or so) is still necessary to reduce switching ripple.

As in the case of power supply design, the introduction of the new switching converter topology solves all of these problems, but the objective of achieving maximum performance (wide bandwidth, low noise and distortion, small (or zero) switching ripple, and low switching frequency), for the minimum number and size of parts, is by no means an easy one.

A New Push-Pull Switching Power Amplifier

We now pose the problem of inventing a power stage, based on the new converter of Figure 5, which will produce an output voltage of either polarity, depending upon a

switch duty ratio D. The design should preserve all the good properties of the new converter previously described and possibly add some more. Since the use of dual power supplies, as in the the buck converter power amplifier, adds to the expense and complexity of the design, the additional feature of a single power supply is desired. Consideration of this requirement led to the discovery of the push-pull type topology shown in Figure 16, in which two bidirectional switching converters are operated in parallel from a single supply.

Let us assume that the two converters are operated switching *out of phase*, that is, with complementary drive ratios. Namely, when switch S_1 is in position A_1 for interval DT_s, switch S_2 is in position B_2 for the same interval. Assuming normal operating conditions, the ideal voltage gain of the top stage is D/D′, and that of the bottom is D′/D. Thus, the two output voltages are equal only for a duty ratio of 0.5, while one or the other becomes greater for other values of D. Evaluating the difference of the two output voltages, $V=V_1-V_2$, gives a differential voltage gain of:

$$\frac{V}{V_g} = \frac{D-D'}{DD'}$$

which is plotted as a function of duty ratio D in Figure 17 (heavy line). The individual converter gains are shown as dotted lines.

As seen in the figure, the differential gain is just the one needed for a switching power amplifier, since it has the same required polarity change property as that of the modified buck power stage (Figure 11). The only trouble, however, is that the load is not across the two converter outputs. Thus, an interesting question arises:

Is it possible to connect a load between the two outputs without violating any basic circuit laws or disturbing the proper operation of the converters?

The answer to this question is affirmative, and is a key to the success of the new push-pull switching power amplifier design. With the two loads in the converter of Figure 16 replaced by a differential ("floating") load R, the new push-pull power stage of Figure 18 is obtained.

In Figure 16, each converter operates independently, with unidirectional current and power flow as shown. However, this is not so in the new push-pull power stage. Owing to the differential load, current originating from one converter must be "sunk" by the other, resulting in equal and opposite current flow, as shown by the solid arrows in Figure 18. With the opposite polarity of the output current, (dotted lines) the roles are reversed. Thus, the switches S_1

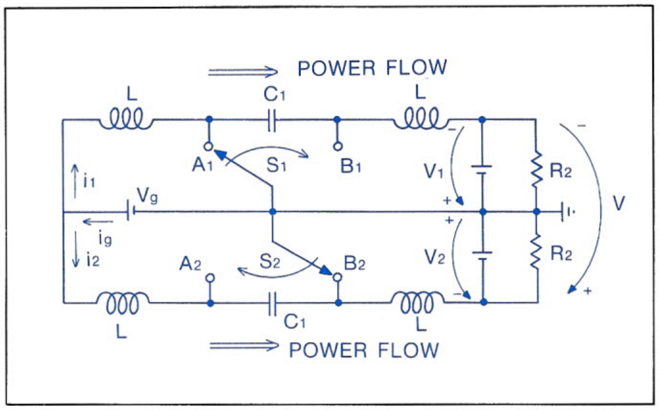


Figure 16. Two bidirectional Ćuk converters operating in parallel from a single power supply.

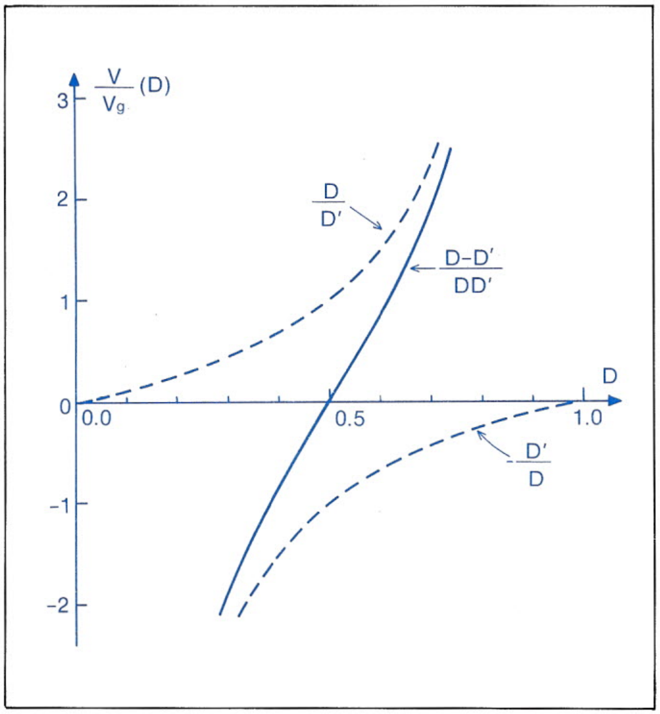


Figure 17. Differential voltage gain V/V_g for the power stage in Figure 16.

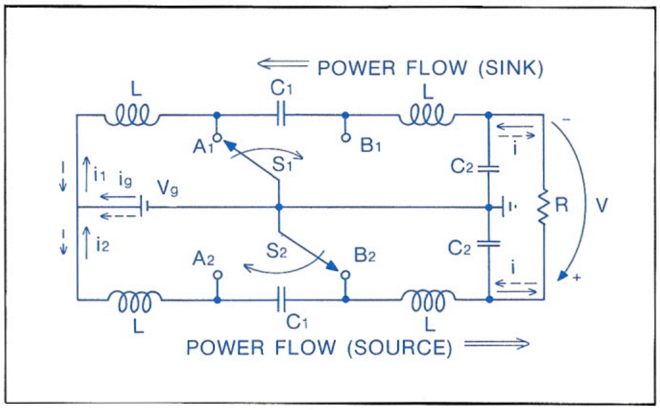


Figure 18. The Ćuk push-pull switching power stage.

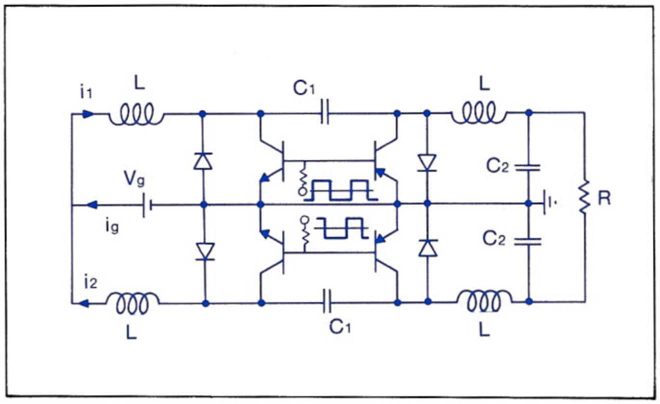


Figure 19. Hardware implementation of the Ćuk power stage.

and S_2 must permit this bidirectional flow, depending upon the duty ratio D. In other words, a part of the energy delivered by one converter is consumed by the load, and the remainder returned by the other to the source. This bidirectional flow is easily accomplished, as discussed previously, as shown in Figure 19.

It may now become evident that the new amplifier power stage may be called a *true push-pull* power stage. Namely, while the lower converter *pushes* the current (and energy) through the load, the upper converter *pulls* it from the load, and vice versa. This is quite unlike the conventional push-pull class B linear amplifiers for which a *push-pull* configuration would be a more appropriate designation.

In addition to the advantages of the bidirectional new converter already described, another very desirable feature derives from this true push-pull configuration itself. Note that since one converter operates as a power sink, the current drawn from the source by the other is reduced

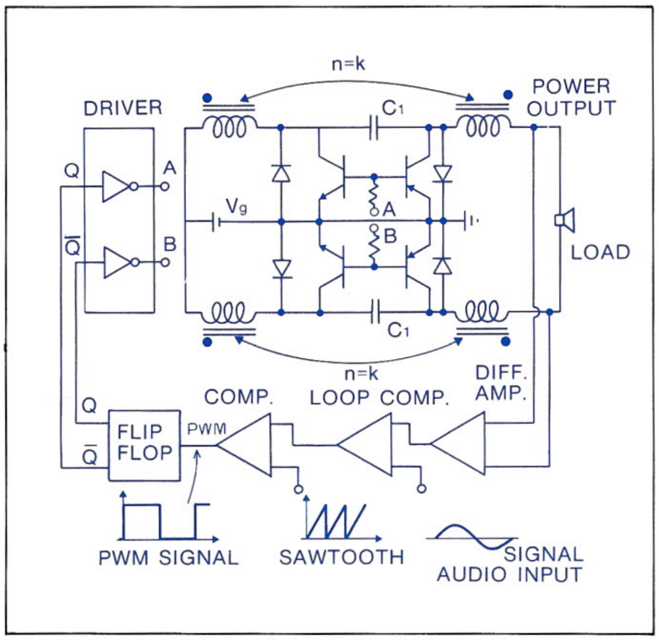


Figure 20. Ćuk push-pull switching power amplifier.

by the return current, (i_2 in Figure 18) which is increasing when S_2 is in position B_2 as shown. (The capacitor is discharging return power into the power supply inductor of converter 2.) Since current i_1 is increasing at the same time, the current ripple through the power supply is reduced. *In fact, if the two inductors on the supply side are equal, the current drawn from the power supply is pure dc with no ripple at all.*

The most advantageous configuration is obtained, however, when the coupled-inductor extension of the power stage in Figure 19 is used. The resulting design is shown in Figure 20, which also represents a complete block diagram of a closed-loop switching power amplifier using the new push-pull configuration. When the two transformers (coupled-inductors) are designed to satisfy the matching condition, as described earlier, the output current ripple, and consequently the need for output capacitors, is completely eliminated. Removing the capacitors results in extremely favorable phase-frequency response and permits closing the feedback loop directly, even without any compensation network, and yet with a high degree of stability. Also, there is no longer any need for an excessively high switching frequency to reduce output ripple, thus resulting in further improvement.

It should be emphasized that the new switching amplifier of Figure 19 is actually based on a new concept of significantly broader scope. Namely, this novel technique of connecting a single dc source to a true push-pull configuration with a differentially connected load may be implemented using any other converter type, as illustrated in Figure 21, provided that the converters are capable of bidirectional current flow and are driven with comple-

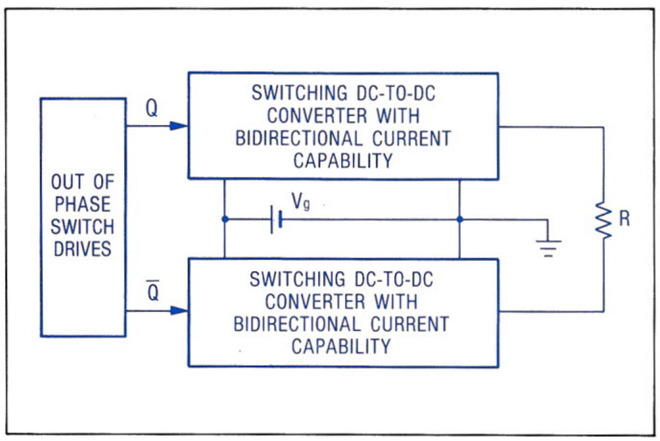


Figure 21. New generalized concept of constructing a switching amplifier power stage from any dc-to-dc converter type.

mentary (out of phase) switching drives. [10] In particular, when this configuration is implemented using two buck-type converters, a single-source power amplifier is obtained even with the buck power stage.

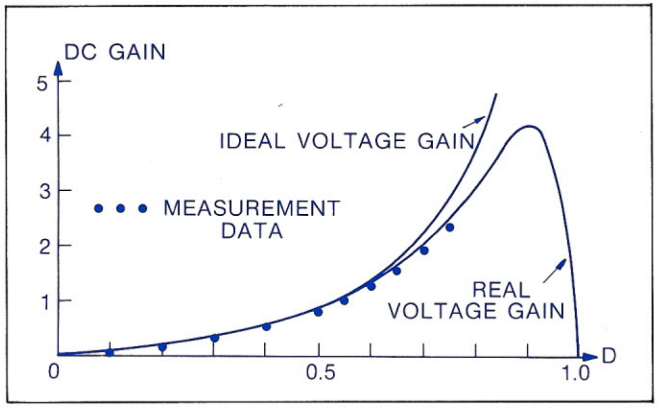


Figure 22. Theoretical and actual dc voltage gain characteristics of a typical test circuit. Experimental measurements confirm the predicted gain curve.

Performance of the New Converter and Amplifier

The new switching amplifier design retains all of the optimal characteristics of the new converter topology, while simultaneously offering improvements due to the push-pull configuration itself. However, one important property of the new design, the linearity of the voltage gain, has not been discussed. Note that although the gain curves of the individual converters in the new design are highly nonlinear, as shown by the dotted lines in Figure 17, the differential voltage is very linear near the duty ratio D=0.5, just where it is needed the most — in the center of its useful dynamic range. Nonetheless, the sources of distortion, as well as the effects of non-ideal circuit elements, must now be addressed to more accurately characterize the performance of the new power stage.

The new converter design has been extensively analyzed and experimentally verified. Limitations to the theoretical dc voltage gain arise due primarily to the effects of the parasitic resistance in the windings of the input and output inductors. Consideration of these terms in the analytical circuit model leads to a predicted voltage gain curve of:

$$\frac{V}{V_g} = \frac{D}{D'}\left[\frac{1}{1+a_1\left(\frac{D}{D'}\right)^2+a_2}\right]$$

where a_1 and a_2 are the ratios of the series resistances of the input and the output inductors to the load resistance, respectively, and R is the equivalent resistance of the load. A plot of this curve for a test circuit is shown in Figure 22, and conforms well to the measured experimental results.

The current gain is unaffected and remains equal to D′/D as before. Thus, the power conversion efficiency for a given duty ratio is equal to the bracketed term in the above expression. As the duty ratio approaches one, the power dissipated in the input inductor grows significant and reduces the operating efficiency of the circuit. The power loss due to the output resistance is independent of the operating point, and becomes the most significant detrimental factor when D is less than 0.5 (voltage reduction).

This model does not consider the effects of other resistive losses that occur because of nonzero voltage drops across the semiconductors (when operating) and the finite switching time they require to become fully conducting. These losses may become significant in applications involving relatively low input or output voltages or high switching frequencies. Nevertheless, all these effects can easily be included analytically by use of the modelling methods described in [7].

When the effects of the parasitic resistances on the performance of the push-pull power stage are included, the differential gain curve of Figure 23 results. As mentioned earlier, the curve for the ideal case (both a_1 and a_2 zero) is fairly linear about the center of the operating region D=0.5. For example, if the variation of the duty ratios in the PWM signal is limited to ± 0.1 (around D=0.5), the resulting total harmonic distortion (THD) in the output will be limited to only 1% [8]. However, a variation of ± 0.2 produces 4% distortion, and increasingly higher THD values result from broader excursions.

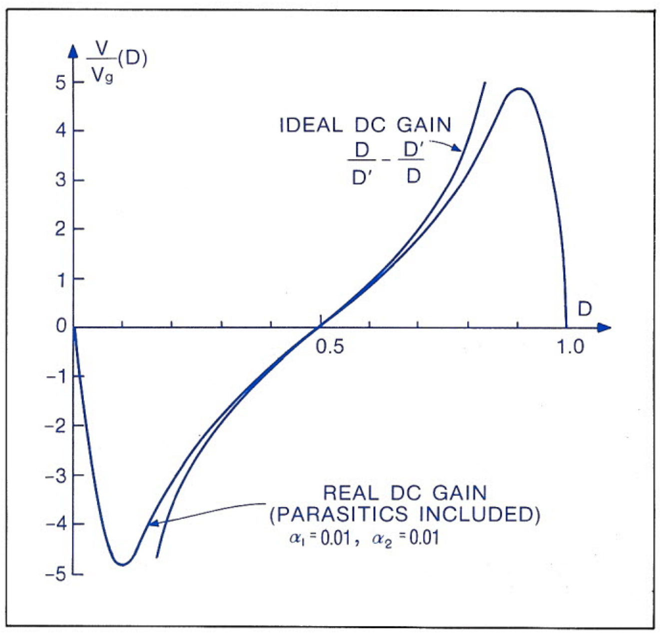


Figure 23. Effective differential gain curve when parasitic resistances are considered.

Furthermore, as can be seen from the figure, the parasitic resistances tend to further linearize the gain around D=0.5. In fact, the values of these resistances can be adjusted to minimize the distortion over the entire operating region. By adding a small resistance in series with the input inductor so that the value of a_1 matches the optimality criterion $a_1=0.0718\times(1+a_2)$, THD can be reduced to well below 0.1% over the range $D=0.5 \pm 0.2$. [8] Thus, almost perfect linearity in the dc gain curve is achieved even without the use of feedback. Although adding an input resistor results in slightly degraded efficiency, test circuits still perform in the 90% range if the variation in the duty ratio is suitably limited. This need pose no unreasonable restriction, however, if the transformer-isolated version of the converter is used [4].

Equally significant is the effect of the series resistance on the frequency response of the new converter circuits. Although each converter stage has three energy storage elements, which could theoretically introduce complications due to multiple resonances, the damping provided by the input resistance effectively produces a highly favorable "single-pole" frequency response. [8] This completely eliminates feedback stabilization problems and allows closing the loop without a compensation network, greatly simplifying design and resulting in even further savings in circuit size, weight, and cost.

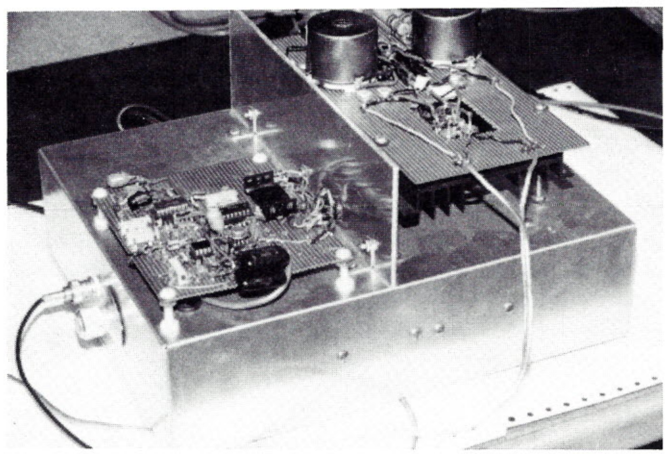
Conclusions

We have shown how a fundamentally new design in switching regulator circuit topology has resulted in dramatically improved performance. The new converter not only offers higher efficiency, low or zero output ripple, and greatly reduced EMI, but at the same time achieves the general conversion function — it is capable of either increasing or decreasing the output voltage depending upon the duty ratio of the switching transistor. The new topology uses capacitive energy transfer between the input and output stages, rather than the inductive energy transfer of other converters, resulting in nonpulsating input and output current. Its implementation requires fewer parts and simpler drive circuitry, with attendant savings in circuit size, weight, and cost.

The excellent frequency response characteristics of the new design allow highly stable feedback regulation to be achieved with simple circuitry. As a result, the basic converter may be used in a new switching power amplifier design that offers performance comparable to linear amplifiers but at much higher efficiency and lower cost — offering, for the first time, efficient dc-to-ac power conversion.

Thus, the new optimum topology converter is superior to any of the currently known switching converters, outperforming them in every respect.

In the next issue of ROBOTICS AGE, we will continue our exposition of the new power converter, describing further extension to the new design for multiple outputs, circuit isolation, and more. Practical design considerations for implementing the converters will be presented, along with schematics and discussions of working circuits. Finally, applications of the converter in power conditioning and motor control will be described.



Prototype version of a Ćuk switched mode audio power amplifier. The circuit delivers 40 watts rms to an 8 chm speaker load, with a flat frequency response over the 20-20KHz range, and over 90% efficiency. A recently built model has been reduced to less than one quarter this size.

Special thanks go to Robert Erickson and William Behen, members of the Power Electronics Group at the California Institute of Technology, for many devoted hours spent in building the first prototype of the new switching power amplifier and the later improvements.

References

[1] Slobodan Ćuk and R. D. Middlebrook, "A New Optimum Topology Switching Dc-to-Dc Converter," IEEE Power Electronics Specialists Conference, 1977 Record, pp. 160-179 (IEEE Publication 77CH 1213-8 AES).

[2] Slobodan Ćuk, "Modelling, Analysis and Design of Switching Converters," PhD thesis, California Institute of Technology, November 1976. Also, NASA Report CR-135174.

[3] Slobodan Ćuk and R. D. Middlebrook, "Coupled-Inductor and Other Extensions of a New Optimum Topology Switching Dc-to-Dc Converter," IEEE Industry Applications Society Annual Meeting, 1977 Record, pp.1110-1126 (IEEE Publication 77CH1246-8-IA).

[4] R. D. Middlebrook and Slobodan Ćuk, "Isolation and Multiple Output Extensions of a New Optimum Topology Switching Dc-to-Dc Converter," IEEE Power Electronics Specialists Conference, 1978 Record, pp. 256-264 (IEEE Publication 78CH1337-5 AES).

[5] R. D. Middlebrook, Slobodan Ćuk, and W. Behen, "A New Battery Charger/Discharger Converter," IEEE Power Electronics Specialists Conference, 1978 Record, pp. 251-255 (IEEE Publication 78CH1337-5 AES).

[6] L. Shaeffer, "VMOS—A Breakthrough in Power MOSFET Technology," Siliconix Application Note AN76-3, Santa Clara, CA (1976).

[7] R. D. Middlebrook and Slobodan Ćuk, "Modelling and Analysis Methods for Dc-to-Dc Switching Converters," invited review paper, IEEE International Semiconductor Power Converter Conference, 1977 Record, pp. 90-111 (IEEE Publication 77CH1183-31A).

[8] Slobodan Ćuk and Robert W. Erickson, "A Conceptually New High-Frequency Switched-Mode Amplifier Technique Eliminates Current Ripple," Proc. Fifth National Solid-State Power Conversion Conference (Powercon 5), pp. G3.1-G3.22, May 1978.

Patents

[9] Slobodan Ćuk and R. D. Middlebrook, "Dc-to-Dc Switching Converter," U. S Patent Application S. N. 837,532 filed September 28, 1977. Also filed in foreign countries.

[10] Slobodan Ćuk, "Push-Pull Switching Power Amplifier," U.S. Patent Application S.N. 902,725 filed in May 3, 1978. Also filed in foreign countries.

[11] Slobodan Ćuk, "Dc-to-Dc Switching Converter with Zero Input and Output Current Ripple and Integrated Magnetics Circuits," U.S. Patent Application S. N. 026,541 filed in March 30, 1979.

[12] Slobodan Ćuk and R. D. Middlebrook, "Dc-to-Dc Converter Having Reduced Ripple Without Need for Adjustments," U.S. Patent Application S.N. 050,179 filed June 20, 1979.

Editor's note: A bound volume of technical papers describing the Ćuk converter and related developments, including most of the references cited in this article, will soon be published. Details will be announced in the next issue of ROBOTICS AGE.

Further development and commercial application of the Ćuk converter has been licensed to a newly formed corporation, TESLAco. (See announcement on page 2.)

About the Authors

Dr. S. Ćuk (pronounced "Chook") obtained his BSEE degree from the University of Belgrade, Yugoslavia, MSEE degree at the University of Santa Clara, and a PhD degree at the California Institute of Technology, where he is at present Assistant Professor of Electrical Engineering, teaching courses in Power Electronics and Energy Conversion.

Dr. R. D. Middlebrook obtained his BA and MA degrees at Cambridge University, England, and MSEE and PhD degrees at Stanford University, California. Dr. Middlebrook is a Professor of Electrical Engineering at Caltech, where he is teaching courses in Electronic Circuit Design.

Profs. Middlebrook and Ćuk are leading a highly enthusiastic group of students and researchers in their Power Electronics Group in a strong effort toward finding new, innovative ways for efficient and controlled conversion of electrical energy, covering the whole spectrum from dc-to-dc conversion to dc-to-ac inversion and power amplification.

PROSPECTS FOR
ROBOTS IN SPACE

Humans are frail creatures, able to exist unaided only in a narrow shell near the surface of the planet Earth. Ten miles from the surface, they would die for lack of oxygen. They would be crushed by their own weight on the surface of Jupiter, frozen by the icy wastelands of Uranus, and vaporized by the high energy plasma storms near the sun. To venture into space, humans must use the most advanced technology to shield them from the deadly surroundings, provide the food, air and water required for life, and guarantee their return to safety.

With all of these difficulties, the question arises: *Do we really need to go out there?* If we extrapolate the present problems of limited resources for a growing world population into the next century, there is an obvious need to seek more attractive alternatives to the radical changes the present trends seem to imply. Although most people regard exploration and expansion into space as mankind's ultimate destiny, the need for sending humans out to risk the hazards of space in order to develop its resources can be reduced and in many cases eliminated by developing machines that can take our place in some of the tasks.

There appears to be no doubt that the space program will shift emphasis from predominantly exploratory activities to primarily public service and industrial activities. According to NASA planning, this requires the construction of large energy collection and transmission stations, and operating space stations either in Earth orbit or on the surface of the Moon. Beginning in the 1980s, the Space Shuttle will enable the first steps toward these goals and hence toward space industrialization by dramatically increasing the possibilities for operations in Earth orbit.

There are many reasons why robots and teleoperated devices should play a major role in space industrialization. Most are the same as those for Earth-based industry—an important one being economy. Conservative estimates of the cost of maintaining a crew in orbit, including launch and recovery, are approximately *2 million* (1978) dollars per year for *each* person. In addition, the results of previous NASA missions indicate that an astronaut can safely perform only one or two hours of zero-G extra vehicular activity (EVA) during each 24 hour period. If attempted by human labor alone, many space systems now envisioned would require the employment of several hundred people in orbit and would consume a large portion of the present NASA budget. It is therefore essential to minimize the number of required personnel in space through advanced

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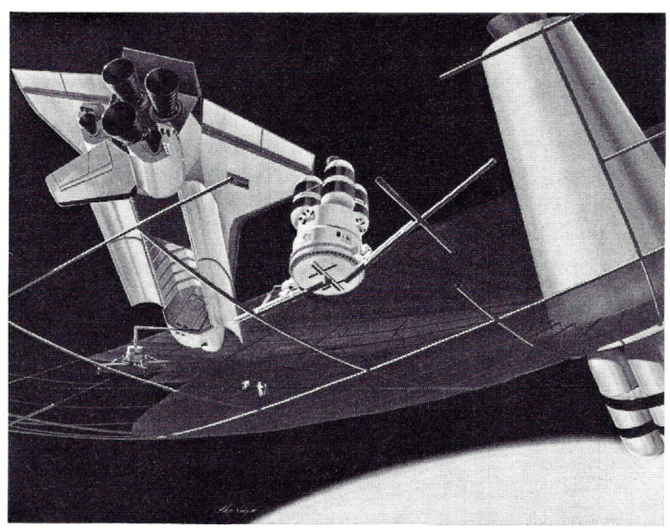
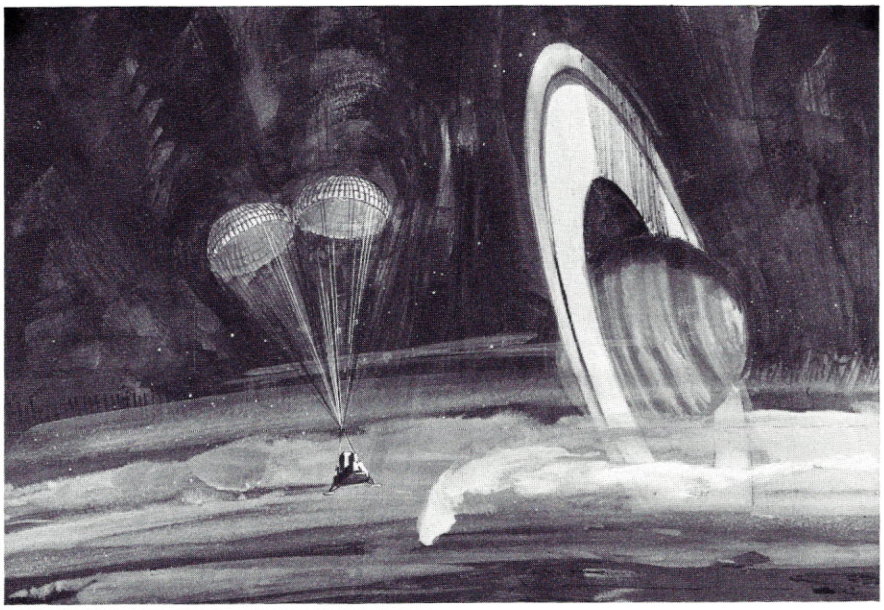
robotics, automation, and teleoperation technology.

Remotely controlled vehicles, such as the early Surveyor moon landers, have played an important role in space exploration. These systems were operated with a "move and wait" teleoperation strategy—the Earth-based controllers of Surveyor had to wait about 2.5 seconds to see the result of their commands. Using a similar strategy to control a device on Mars would require up to 40 *minutes* per movement. As we venture further into space or attempt to perform complex tasks, our mechanical agents must therefore have an increasing degree of autonomy. Limited opportunities for communication, together with reduced information volume and transmission delays, require increased capabilities on board the space craft.

The use of teleoperation involves other considerations as well. Studies show that the human controllers tire quickly under the demanding work load, depending upon the complexity of the task and the available display information. Also, the vehicle is useless during communications blackouts, and data channels which could be used to return valuable science information must instead be used for vehicle control feedback. For interplanetary missions in particular, deep-space communications are



In this scene of possible future space work, robotic machines, supervised by astronauts, assemble a giant radio telescope antenna in low Earth orbit. Structural components of the antenna are aligned and joined by a free-flying robotic tool, and a second, mounted on the end of the Space Shuttle's manipulator, installs a reflective panel.



Saturn's rings are not its only attraction. One of the gas giant's moons, Titan, is remarkably Earth-like, with a heavy atmosphere. To investigate this phenomena and probe for possible life-forms, NASA/JPL scientists would like to land a Viking-type experiment package there in the late 80s. Such a mission would require considerable automation, both for the orbit and landing phases as well as sample acquisition by a robot manipulator.

restricted by the limited number of ground stations that must service several ongoing missions. Alternatively, when the human operators are located in space, as proposed for some space construction projects, there is the additional expense of their transport to and from orbit and their environmental support.

By their exceptional performance in recent deep-space missions, interplanetary spacecraft such as the recent Viking Mars Lander have begun to demonstrate the potential of on-board "intelligent" control. Whereas earlier spacecraft computers were limited to carrying out actuator sequences completely predetermined by programmed instructions, the Viking Lander was able to descend from Mars orbit and adapt to the largely unknown characteristics of the Martian atmosphere, monitoring its altitude and computing the thrust and attitude needed for a successful soft landing—entirely without human intervention.

The growth in capability of on-board controllers will enable missions that were either technically or economically infeasible before. As in the case of the Viking Lander, many of these missions involve making the appropriate decisions quickly in response to observed conditions, in circumstances where control from Earth is not possible due to the need for real-time action. In this category are a number of unmanned scientific and exploratory missions such as rendezvous with an asteroid or with Halley's comet (which returns in 1986), or landing on a satellite of one of the outer planets.

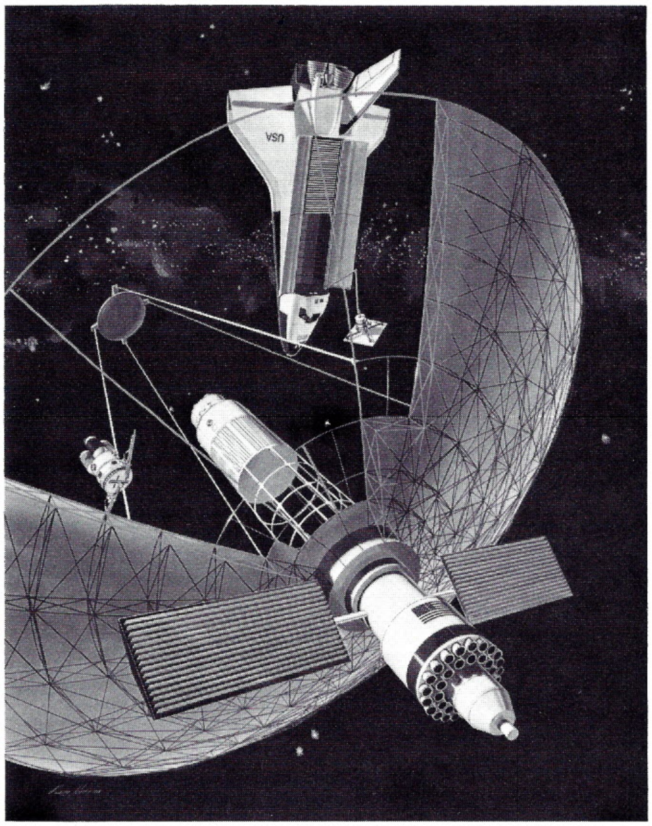
A planetary roving robot with the ability to select and follow a safe path through uneven terrain could reduce the requirements for human control to a minimum, substantially reducting operations costs during the mission while maximizing its scientific value. A recent study for a potential Mars Rover mission determined that such a robot could remain active over 80% of the time, whereas with Earth-based teleoperation the vehicle could travel only about 4% of the time. We will examine this particular mission in greater detail later.

The Utilization of Space

The industrial revolution is still continuing throughout the world. It is only in its first phases in many developing nations and in varying stages of a new phase in the United States and other already industrialized nations. This new phase is characterized by the application of advanced technology to attain increased productivity and standards of living. Perhaps its most outstanding features are the spectacular recent development of electronics, particularly its use in computers and industrial automation. [1] The next phase of the industrial revolution is already taking shape in the space program, leading us in the direction of a new frontier—a frontier hardly more than 100 miles away!

The bridge to this frontier is the Space Transportation System (STS)—the Space Shuttle and its adjuncts—which is expected to propel the space program into an era of rapid expansion, particularly in industrial activities. The STS will make accessible on a broad scale the special environmental properties of space—zero gravity, hard vacuum, a limitless supply of clean energy, and a high vantage point. It will also lead to the first steps in this new territory toward the exploration and utilization of resources from the moon and the asteroids for the social and economic benefit of people on Earth. These benefits will be in the form of new services, new products, and new sources of energy. In a recent study, more than *two hundred* opportunities for industry in space have been identified. (See Table 1.) As space industrialization progresses, many as yet unforseen opportunities will be discovered.

On a broad scale, space industrial opportunities can be



classified into four main areas, pertaining to information handling services, energy production, materials and products, and services for people in space. We will briefly examine each of these categories, first with regard to their potential benefits and later in terms of the automation technology they will require.

Information Handling

The area of space-based information handling services is already a reality. For several years, satellites have been providing valuable communication, navigation, observation and weather services for people throughout the world. Today communication satellites are owned and operated by more than a dozen countries, and more than 100 have their own ground terminals for the International Telecommunications Satellite (Intelsat).

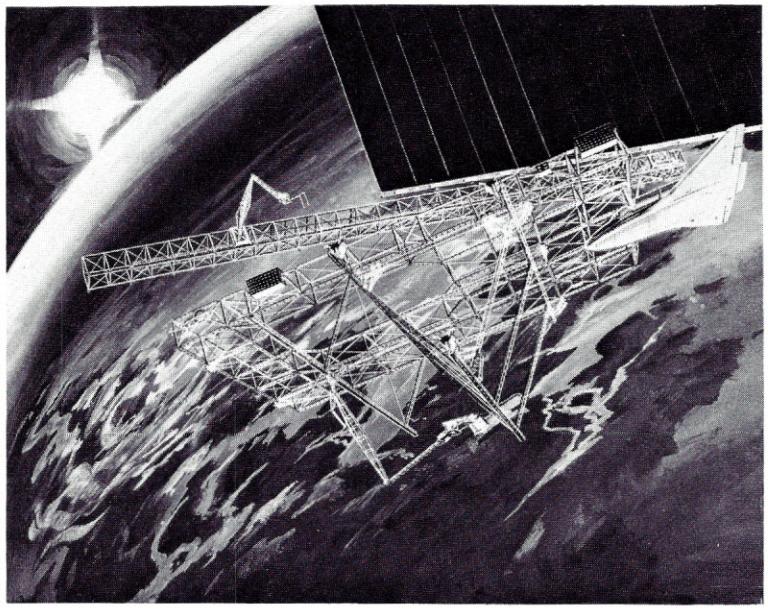
But this is only the beginning. By developing the capability to construct extremely large *multibeam antennas* in space, one can broadcast preprocessed information directly to the individual user. [3] Multibeam technology will enable many advanced communications systems—pocket telephones, direct broadcast TV, electronic teleconferencing, and many other applications will soon become practical and cost-effective. Along these lines, the concept of *telecommuting*, as well as teleoperation, will allow workers to interact electronically with people and machinery from their homes, introducing a new lifestyle and also saving considerable energy and time now spent for transportation.

With the ability to process their observational data onboard, the effectiveness of surveillance satellites will increase tremendously. These orbiting robots collect data for public service use on soil conditions, oceanographic measurements, global crop conditions, weather, geology, disasters, and many other observables. Of the immense volume of data acquired, usually pictorial, only a fraction is information of interest to the ultimate user. For systems now in use, the data must be sent to the ground, where it is processed, reduced, analyzed, and distributed to the user. For some satellite photographs this requires up to three months, and the fully processed image costs *several thousand* dollars.

Present developments in machine intelligence and robotics suggest that, in the future, much of the ground-based data processing and information extraction can be performed on board the robot spacecraft. Only the useful results would be sent to Earth, while most data would be discarded immediately. To achieve this, the robot vision system must be programmed or trained to recognize significant features in routine scans. Upon detecting something of interest, it could perform a more extensive

INDUSTRY	AGGREGATED PRODUCTS/SERVICES	NUMBER OF USES
INFORMATION		
COMMUNICATIONS	INDIVIDUAL 2 WAY, GROUP 2 WAY, DOWN/UP LINK ONLY, REMOTE CONTROL	25
OBSERVATIONS	ENVIRONMENTAL, RESOURCES, SURVEILLANCE	19
NAVIGATION	AERIAL, NAUTICAL	3
LOCATION	INDIVIDUAL, PACKAGES/VEHICLES	9
SENSOR POLLING	INDIVIDUAL, GROUPS, AUTOMATED	11
ENERGY		
SOLAR POWER SATELLITE	ELECTRIC POWER, HEAT	2
REDIRECTED INSOLATION	HIGH INTENSITY, LOW INTENSITY	5
NUCLEAR WASTE DISPOSAL	LONG TERM SAFETY	1
NUCLEAR POWER SATELLITE	ELECTRIC POWER WITH LONG TERM SAFETY, NUCLEAR MATERIALS	2
POWER RELAY	ELECTRIC POWER DISTRIBUTION, AIRCRAFT POWER	3
MATERIALS/PRODUCTS		
BIOLOGICALS	SEPARATION/PURIFICATION, CULTURING	8
ELECTRONICS	SEMICONDUCTORS, RECTIFIERS, DEVICES	11
ELECTRICALS	MAGNETS, WIRING, DEVICES	19
STRUCTURAL MAT'LS	IMMISCIBLE ALLOYS, FLOAT ZONE REFINING, DIRECTIONAL SOLIDIFICATION, COSTING, JOINING COMPOSITES	62
PROCESS MAT'LS	CATALYSTS, MEMBRANES, POWDERS, DEVICES, PURIFICATION	23
OPTICALS	FIBERS, LENSES, FILTERS, SPECIALTY ITEMS	24
EXTRATERR. MAT'LS	ALL ABOVE WHERE COMPATIBLE, RAW MATERIALS	
SERVICE TO PEOPLE		
ORBITAL TOURISM	SHORT TERM (DAYS), LONG TERM (WEEKS), TRANSPORT	5
MEDICAL	ISOLATION, TREATMENT, AUGMENTATION	5
ENTERTAINMENT/ARTS	OBJECTS (FROM SPACE), ACTIVITIES (IN SPACE)	6
RECREATION	AMUSEMENT PARK, LODGING	3
EDUCATION	IN SPACE CLASSROOM, CLASSES FROM SPACE	3
SUPPORT	SOCIAL ISOLATION, ECOLOGICAL ISOLATION	6

Table 1. More than 200 possible uses of resources and facilities in space have been identified in recent studies. Robotics and automation will play a key role in making space industrialization practical.



Space structures such as the Space Solar Power Satellite, whose construction is depicted here, will be larger than any structure on Earth. Their assembly will require the use of robots and man-machine systems that fabricate the immense structural members, position them accurately, and fasten them into place.

analysis and contact the appropriate ground station to report its findings. The user would be able to interact with the robot from a remote terminal to request special actions, achieving the rapid response necessary to evaluate short-lived conditions such as forest fires or hurricanes.

Energy Production

Space solar power holds great promise for providing a new source of clean, safe, and abundant energy. It offers the potential to approach energy self-sufficiency. Space industrialization technology can provide perhaps its greatest benefit through the large-scale exploitation of the Sun's energy. The Space Solar Power Satellite (SSPS) is perhaps the best known example. The energy that can be intercepted and then beamed to Earth by a SSPS exceeds the amount that can be collected by a facility of similar area located on the ground by about an order of magnitude.

The collector surface of an SSPS would be larger than any structure on Earth. A cost-effective system would be over *ten kilometers* in length, and surfaces of up to 100km^2 are being considered. Their construction and subsequent maintenance will require technologies not yet in use on Earth. It will be essential to reduce the cost of such a project by performing as much of the construction task as possible with robots. Even the basic structural components will most likely be manufactured from bulk materials by specialized automated machines on an orbiting construction platform.

NONFUEL DEMANDITE COMPARED TO ELEMENTAL DISTRIBUTION FROM ONE MOON SITE

ELEMENT	WEIGHT FRACTIONS	
	NONFUEL DEMANDITE	APOLLO 15 MARE (LOW TITANIUM)
SILICON	0.2444	0.2158
OXYGEN	0.4547	0.4130
IRON	0.0479	0.1535
ALUMINUM	0.0023	0.0546
MAGNESIUM	0.0017	0.0681
COPPER, ZINC, AND LEAD	0.0020	0.000022
(a)	0.0030	0.0189
CALCIUM	0.1417	0.0696
SODIUM	0.0095	0.0023
SULFUR	0.0058	0.0006
POTASIUM	0.0021	0.0008
PHOSPHORUS	0.0019	0.0005
CHLORINE	0.0147	0.0000076
NITROGEN	0.0083	0.00008
CARBON	0.0574	0.000095
HYDROGEN[b]	0.0025	0.000070
TOTAL	0.9999	1.0000

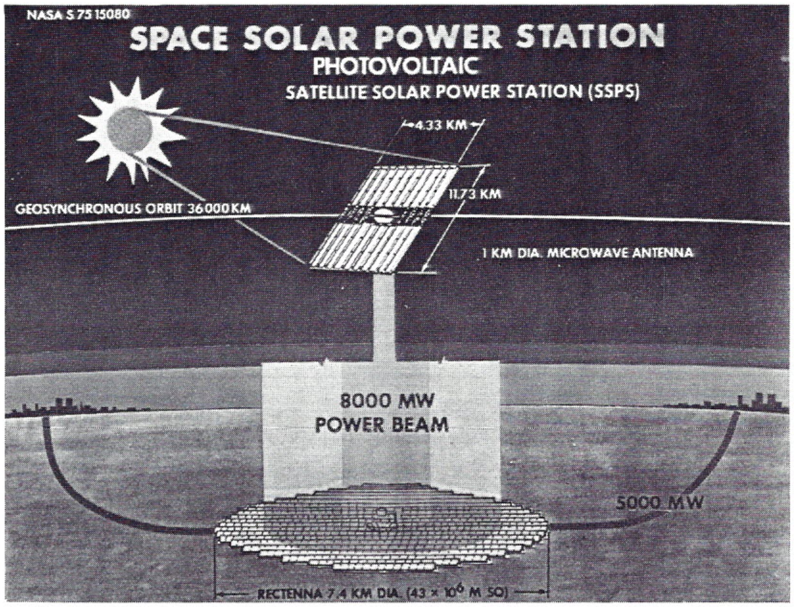
(a) MANGANESE, TITANIUM, CHROMIUM, BARIUM, FLUORINE, NICKEL, ARGON, TIN, BROMINE, ZIRCONIUM, AND BORON.

[b]FOR USE IN PLASTICS; DOES NOT INCLUDE WATER.

Table 2. Analysis of soil samples returned by Apollo 15 indicate that most of the non-fuel resources required by society can be supplied by processing lunar materials.

Material Products

There are two main end uses for material products in space. In addition to the construction of structures and facilities in orbit, an important activity will be the development and application of advanced material processing technologies that exploit the peculiar environmental characteristics of space for the manufacture of products for use in space or for return to Earth. Several basic types of these processes are currently envisioned. For example, in zero-G it is possible to solidify molten compounds without convection flow or sedimentation and even to process molten samples without containers. Other examples are isotropic diffusion in liquids and vapors and electrophoretic separation of biological substances. It is expected that specialized automated instrumentation will be devel-



The energy delivered to Earth by a SSPS would exceed that produced by a ground facility of similar size by an order of magnitude. Power would be transferred from orbit in the orm of microwaves and received by an antenna array on the ground. The energy density of the beam would be so low as to be harmless to humans or passing aircraft.

oped for the remote control of these processes once their particulars are worked out and the pressure of commercial requirements becomes noticeable.

Projecting current trends into the next century, it appears that the terrestrial resources of high-grade ores are heading toward depletion. This may render considerably attractive the alternative of mining the Moon or the asteroids for such materials. The first use of non-Earth resources will most likely be in the construction at geosynchronous orbit of a specific large-scale project such as the SSPS. Once begun, however, a more diverse space industry could develop which would both expand the availablility of materials and products as well as decrease their cost in space, eventually making their return for use on Earth a practical enterprise.

To evaluate whether a complex industrial base could be supported with extraterrestial resources, th concept of *demandite* has been useful to characterize the material requirements of an industrial economy. [4] The term has been applied to the composition of the total nonrenewable resources used in the United States. In Table 2, the components (other than fuel) of terrestrial demandite are compared to the distribution of elements found in samples from the Apollo 15 lunar site. [5] The comparison shows that more than 90 percent of the materials required for a complex industrial society are available from average lunar soil with little or no enrichment.

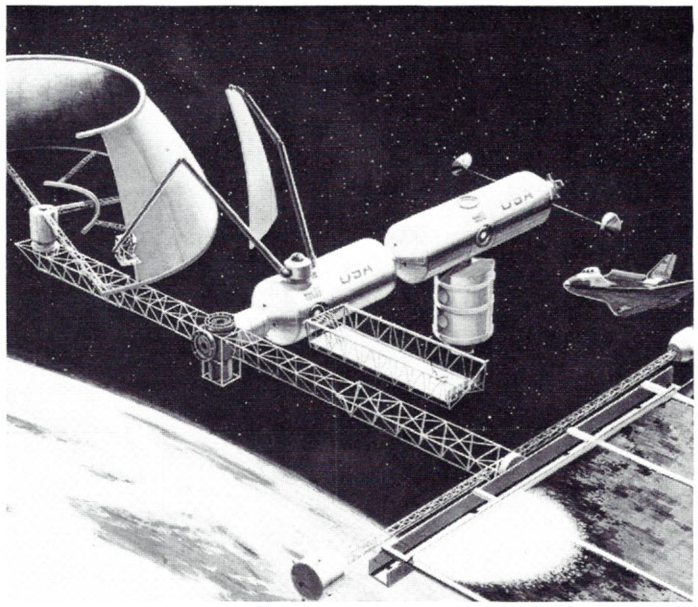
A first step towards the exploitation of lunar resources may be establishing an automated material processing system on the Moon. After a survey by robot vehicles to select the most suitable site, such a system would collect solar energy and use it in automated physical and/or chemical processes for extracting volatiles, oxygen, metals, and glass from lunar soil delivered by the robot rovers. The products would be stored, slowly building up stockpiles in preparation for a lunar base. As in the case of orbital construction, the lunar base would be built using automated equipment and robots. After its completion, general-purpose robot devices would be necessary for maintenance and repair operations. In addition, the base would employ all types of industrial automation commonly used on Earth for similar tasks, suitably adapted for operation in space.

In-Space Services for People

Certainly the most popularized of our future activities in space are those that involve creating safe environments for substantial numbers of people in orbit. With the advent of technologies for the construction of large space structures, many possibilities for exploiting the weightless environment will arise. For certain medical procedures, such as those for treating victims of severe burns or various kinds of physical therapy, zero-G conditions would be ideal. With the many recreational possibilities of weightlessness, one can easily envision that the tourism industry could be augmented by flights to space stations with comfortable habitats.

Recently, considerable attention has been devoted to Gerard O'Neill's concept of self-supporting space colonies at the Lagrange libration point L5 in the Earth-Moon system. [6,7] Objects at this location orbit the Earth at a fixed position relative to the Moon. The proximity of this stable location to the Moon makes lunar mining a feasible, even essential factor in the strategy for creating such a colony. All the possibilities previously outlined for space construction and lunar mining have direct application to achieving this goal.

One of the most fascinating ideas for the future utilization of space is the concept of *self-replicating* robot systems. As in the case of the automated lunar materials processing system described earlier, these systems would use as raw materials the resources available on a planet's



surface. However, instead of merely stockpiling refined materials and products, the robots would use them in the construction of yet *additional* robots and capital equipment. Manufacturing capability would thus be expanded using the planet's own resources, minimizing the requirements for importing goods and materials from Earth. This concept introduces the prospect of creating the basis for a self-supporting economy by robot labor, so that human immigrants from Earth could venture forth with a minimum of risk, feeling secure in knowing that the means of their continued survival has already been provided before their arrival.

Technology Requirements for Automated Space Systems

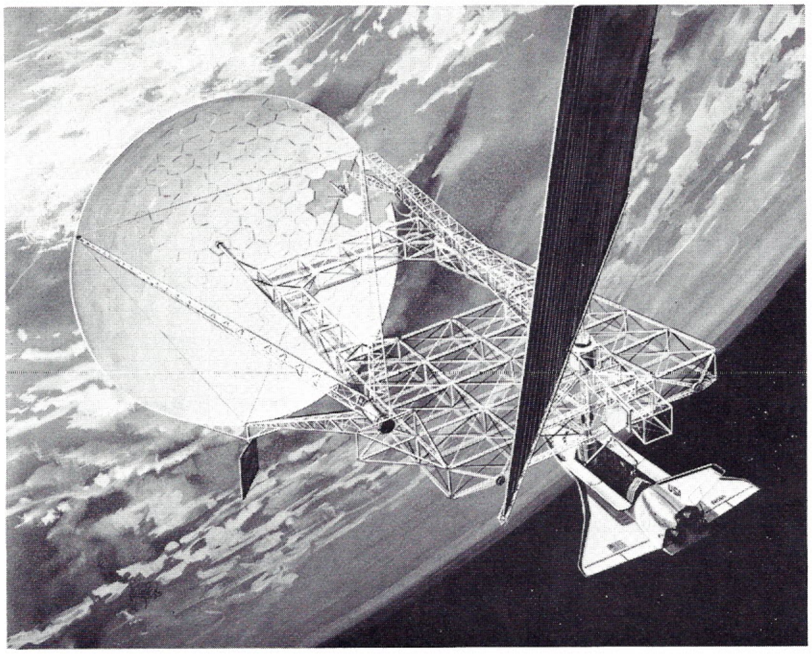
The automated devices that will be needed for the effective utilization of space will vary greatly in the degree of human involvement necessary for their operation. At one extreme, they could be completely remote-controlled like conventional teleoperator devices. Alternatively, they could be under *supervisory* control, needing guidance from a human operator only intermittently. Between these extremes lies a broad range of computer-assisted operation. Astronauts in space or human operators on Earth will need such aids to accomplish the envisioned programs. The technology which needs to be developed will provide the foundation for the evolution of these space-age tools.

Many of the tasks currently being investigated require the development of space-qualified manipulator systems. As shown in the figures, the structural elements of space platforms will be handled by large teleoperated or self-acting manipulators comparable to cranes, which bring the members or subassemblies into the proper position for joining. The joining operation requires precision alignment and fastening. Thus, both a high-quality general-purpose handling capability and specialized automated fixtures are required. The movement and joining of large structural subsystems normally requires rendezvous, station-keeping, and docking operations at several points simultaneously and with high precision—a problem area still not investigated for zero gravity orbital conditions.

A capability that is essential to all advanced robot concepts is the complex sensory processing required to interpret video (and other) images. Both orbiting global service satellites and space construction robots require a sense of vision to locate and identify parts or features in the fulfillment of their functions. In some assembly tasks, successful performance will depend upon the ability to rapidly process TV images to guide the movement of components by visual-feedback servoing. Mobile robots that operate on a planetary or lunar surface must be able to determine the traversability of terrain, so that a safe path around obstructions or hazards can be followed.

In addition to vision, devices for automating the assembly operations needed for space construction must have a well-developed sense of touch. Functions such as inserting a structural member into a closely fitting receptacle require feedback that indicates the direction and magnitude of the contact forces. This feedback is essential whether the device is operated by computer or by human control. The introduction of "intelligence" into tools that are used by humans will be an important means of increasing the effectiveness of astronauts encumbered by inflated space suits. These may range from automated torque wrenches to sophisticated joining tools that grasp components, align them precisely, and operate a fastening mechanism.

Robot systems that operate without continuous human supervision require control programs that can adapt the robot's behavior to changes in the environment in order to effectively accomplish its goals. For some robots, such as the Viking Lander described earlier, the range of behavior



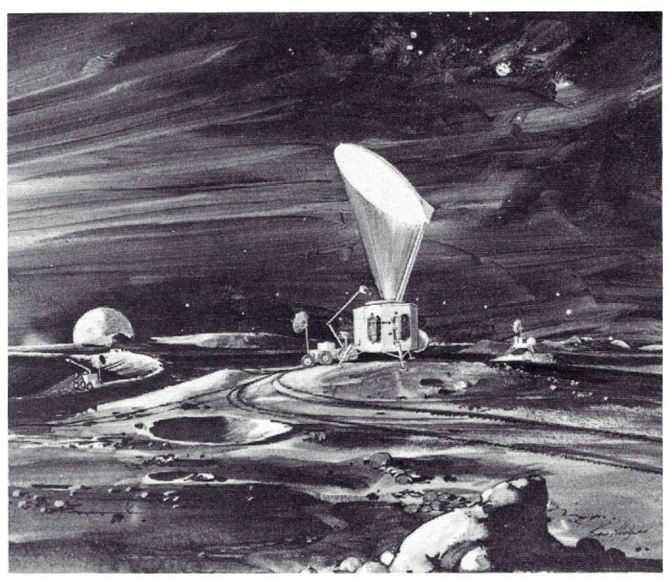
required may be expressed in a human-supplied program that completely determines the system's response to sensed conditions. However, when complex behavior is required, as in space or planetary construction operations, it becomes desirable to give the robots the ability to "intelligently" plan a course of action by choosing from a broad range of possible strategies.

Recent research in Artificial Intelligence suggests the possibility of providing a robot with a basic knowledge of cause and effect that describes the expected outcomes of a large collection of possible actions. Using such a store of knowledge, future robots may be able to select a sequence of actions that are appropriate for a given situation, achieving the desired results without violating other goals or constraints. Such an ability will greatly extend the generality and autonomy of the devices beyond what would be possible with hand-coded control programs alone. In work at the Jet Propulsion Laboratory, these techniques are already being applied to aid in the design of command sequences for currently planned deep-space missions.

Other current development programs will provide a sound basis for the advanced systems needed for future projects. An example is the control system for the Remote Manipulator System (RMS) to be used by planned Space Shuttle missions. This man-machine system will perform much of the computation needed in order to grasp payloads that are in motion relative to the Shuttle. The system will allow the astronaut-controller to operate the RMS as if the payload were stationary by automatically matching its relative velocity. In addition, several automated aids tell the operator when a secure grasp is possible and perform part of the grasping process.

In the area of planetary operations, a recent study for a proprosed Mars Rover mission concluded that a robot vehicle would be capable of performing autonomous traverses of the Martian terrain. [8] Once given a sequence of checkpoints along a recommended path, the robot would use a combination of laser rangefinder and visual scanning to locate and avoid rocks and fissures. Travelling as far as two kilometers per day, it would need to transmit to Earth only once to send back science results and images of the surrounding terrain where it stopped. After receiving a new set of checkpoints, it would resume its autonomous traversal for another day.

This mission profile meets many of the requirements for



A solar-powered material processing station on the Moon would be supplied by soil brought by robot rovers. The automated station could produce oxygen, water, and building supplies to be stockpiled for an eventual lunar base.

future space operations using robots. The on-board intelligence minimizes both the volume of communications and the ground support personnel needed during the mission. The robot would be able to cover 100 meters each Martian day, travelling over 100km during its nominal lifetime of one Martian year (two Earth Years). In its Site Investigation mode, scientists would be able to designate selected rocks or soil samples for acquisition by the robot. Given only the location of the sample in an image, the robot would be able to plan a safe trajectory for its manipulator to collect the sample and deposit it in the proper experiment hopper. By contrast, the manipulator used in the Viking mission required a team of human programmers to determine a safe sequence and was unable to recover from any execution error.

Conclusion

The advanced technology necessary for our future in space will soon begin the difficult transition from laboratory experiment to practical application in the space program. It is impossible to enumerate the many potential benefits of this effort on our future standard of living. Nevertheless, the requirements for applying robot and automation technology to the utilization of space derive from the same considerations as for Earth-based industrial activities and are justified on similar grounds. Clearly, more definitive studies on the tradeoffs of developing such technology versus the cost of supporting human workers in space are needed.

Given the economic pressures motivating the growth of industrial automation, capabilities similar to those described here will eventually be realized for use on Earth. On this basis alone, their ultimate application to space industrialization is assured. The availability of the Space Shuttle and the need for increased automation in scientific space missions provide many opportunities to hasten this exciting and rewarding reality.

References

[1] E. Heer, "New Luster for Space Robots and Automation", Astronautics & Aeronautics, September 1978.

[2] E. Heer, "Robot and Automation Technology Requirements for Space Industrialization", Proceedings of ISIR9, Washington, DC, March, 1979.

[3] I. Bekey and H. Mayer, "1980-2000—Raising our Sights for Advanced Space Systems," Astronautics & Aeronautics, July/August 1976.

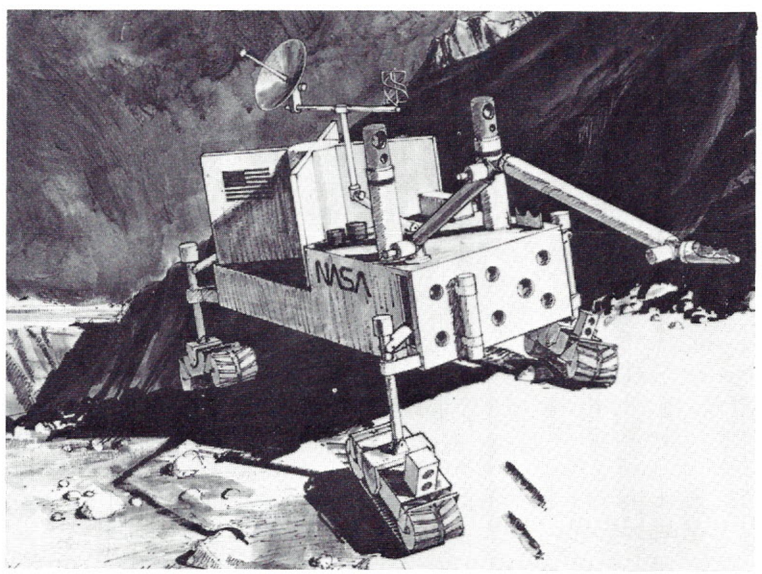
[4] D. R. Criswell, "Demandite, Lunar Materials, and Space Industrialization", 3rd Princeton Conference on Space Manufacturing, Princeton, NJ, 1977.

[5] J. R. Arnold & M. S. Duke, Eds, Summer Workshop on Near Earth Resources", NASA Conference Publication 2031, NASA Scientific and Technical Information Office, 1978.

[6] G. K. O'Neill, *The High Frontier*, New York, Morrow (1976).

[7] R. D. Johnson, "Space Settlements—A Design Study", NASA SP-413, NASA Scientific and Technical Information Office, 1977.

[8] B. Dobrotin, et al, "A Design for a 1984 Mars Rover", 16th AIAA Aerospace Sciences Conf., Huntsville, AL, January, 1978.



A Mars rover such as this is possible with today's robot technology. The robot would be able to navigate safely around rocks, slopes, and fissures using information obtained from on-board processing of video and laser images. Samples selected by scientists from images sent back to Earth would be automatically acquired by the robot and deposited in its test chambers.

ROBOTICS RESEARCH IN JAPAN

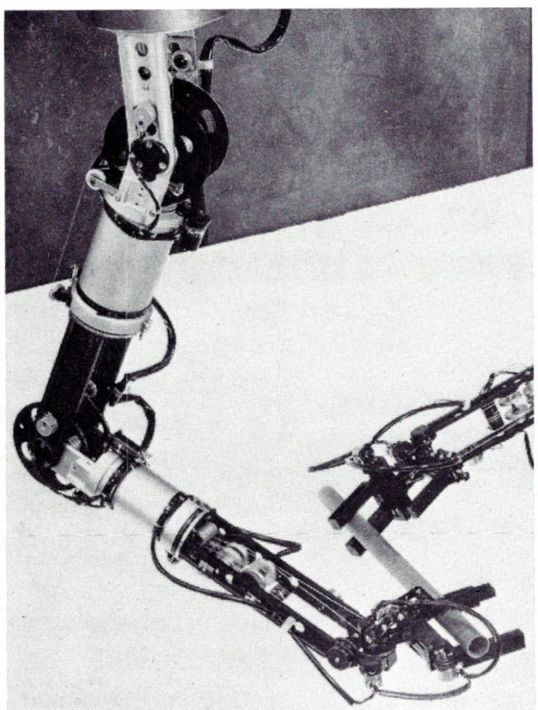


Figure 1. This ETL experimental robot performs tasks requiring the cooperation of two arms. Each arm has seven joints, and the end-effector has two degrees of freedom for grasping.

FORCE CONTROL OF A MULTI-JOINTED ROBOT ARM

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Control of the forces applied by the manipulator to objects in its workspace is essential for many practical applications involving constrained movement or delicate parts. Whenever a part is pushed, the forces caused by its connection or contact with other objects provide information that is important for the success of the task. A robot trying to assemble pieces given only their positions in the completed assembly may try to force them together without regard to resistance. If a part jams, the force may be increased to the point where damage occurs either to the part or to the manipulator. Also, errors or uncertainty in the machine's knowledge may cause unexpected results — if a window is not where a position-controlled robot believes it is, collision and breakage may result from an attempt to apply a sponge.

Normally, this shortcoming is due to the limitations of

(continued page 32)

Industrial robots have found widespread application in Japanese manufacturing, and have already become a key factor contributing to productivity. Almost all industrial robot manufacturers, both in Japan and abroad, have research programs designed to increase the capabilities of their systems and to find new applications, but there is also a need to pursue advanced robot concepts that may require considerable development before becoming practical for commercial application. Although this research is essential to the advancement of the field, because of its long, uncertain payback period it is usually left to academic institutions and government sponsored contractors and research labs. A key component of advanced robots is a manipulator that can be programmed for a wide variety of tasks. This requires an ability to control not only the position of the robot arm, but the contact forces it applies to objects — allowing the robot to measure friction, to move the end-efffector along constrained paths (as in turning a crank or opening a door), and to perform many other jobs that need the right "push" in the right direction. These skills are essential for most parts assembly problems. Together with more versatile mechanical designs for the arm and its end-effector, enhanced force-control capabilities will lead to the general purpose robot of the future. In Japan, research in this direction is being performed at the Electrotechnical Laboratory (ETL) of the Japanese Ministry of International Trade and Industry. Researchers at the ETL are actively pursuing goals in many aspects of robotics and machine intelligence. The following two discussions present experimental robot manipulators recently developed at ETL, both demonstrating innovations in mechanical design and control technique. We wish to express our gratitude to the authors and to ETL for their kind cooperation in providing technical material for this article.

A VERSATILE END-EFFECTOR WITH FLEXIBLE FINGERS

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Although the dexterity of human manipulation can hardly be equalled by conventional machines, advanced automation systems will require an extremely versatile mechanical hand. In many manual tasks, such as assembling complicated parts, the utility of industrial robots has been limited because of the lack of flexible motion in their manipulator end-effectors. Present designs may have a suitable shape for grasping a particular class of parts, but because of their vise- or jaw-like structure, control of the relative orientation of the fingers and their grasping force has been limited. Even in designs featuring fingers with multiple joints, the joints are typically coupled to move in unison, precluding complex movements such as those required for manipulating an object while holding it.

Even though the complexity of human sensory-motor capabilities has not yet been attained, many of the

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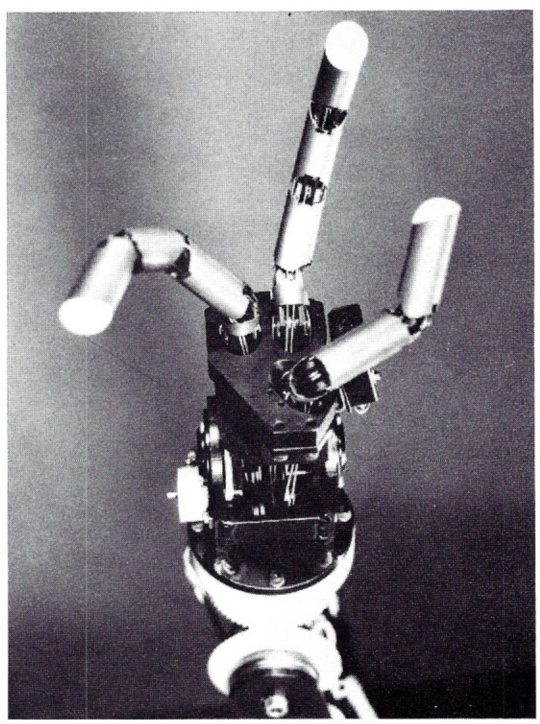

Figure 1. The ETL experimental anthropomorphic end-effector is capable of a wide range of movements. Its three fingers are structurally similar to the human thumb, index, and middle fingers.

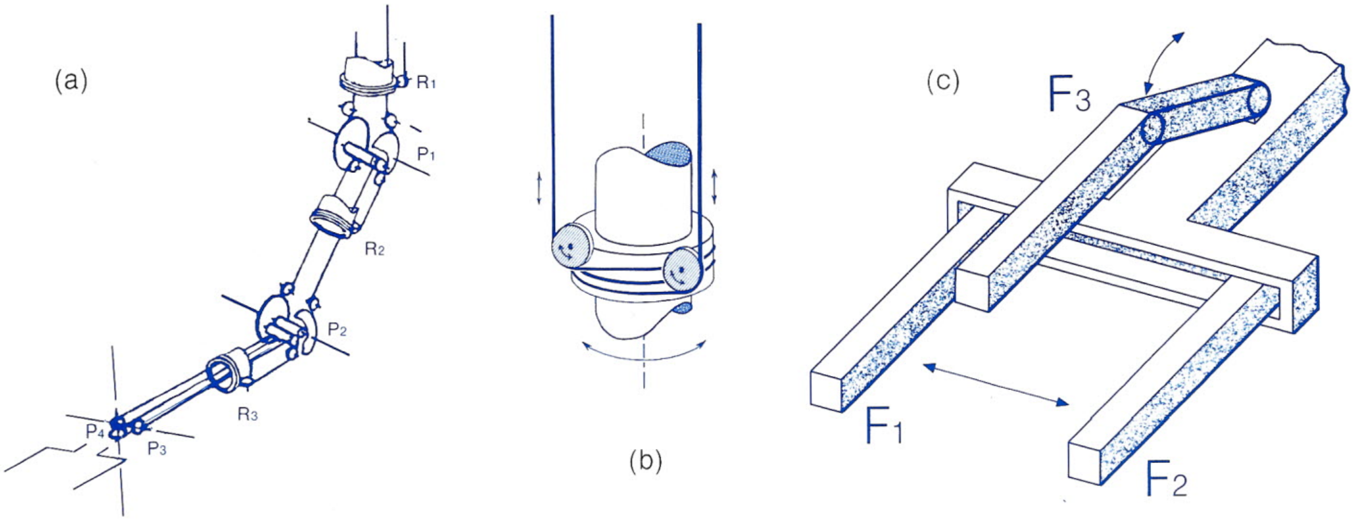

Figure 2. Mechanical construction of the manipulator, showing (a) the degrees of freedom in the arm, (b) the method of driving rotational joints with tension cables, and (c) construction of the end-effector.

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the servomechanism control design, the mechanical design, or both. Robot manipulators using position servos control the arm's motion by setting the value of the joint angle of each link. This results in stiffness, preventing the arm from easily adapting to external forces and making force-related tasks such as driving a nail with a hammer or inserting a peg in a hole very difficult to perform. Moreover, the simultaneous coordinated movements of two manipulators working in unison require that each arm must be able to respond appropriately to forces caused by the other. In short, even a robot with "artificial intelligence" providing the ability to sense its environment and plan appropriate responses would be seriously limited without comparably advanced motor skills.

In the new generation of computer controlled manipulators, control of arm movement is accomplished by direct computer control of the torque applied to each joint. These torques are computed by software servo algorithms that consider the forces required for the effective interaction of the arm with the environment as well as the arm's position and velocity. Already, systems have been developed that can accomplish complex insertion tasks by the use of special purpose tools. [1, 2, 3] In many cases, however, the skills provided by the special mechanisms can also be accomplished in the software servo by using adaptive force control, thus replacing the physical mechanism by a "virtual" mechanism implemented in software. In this way, the "tools" and skills of the robot can be changed by software, increasing its generality and ease of application. [4]

Another consideration is the ability to control the configuration of the arm within the workspace. To position the end-effector at a desired point in a three-dimensional workspace requires three degrees of freedom, normally realized by three arm joints. The ability to orient the end-effector in a desired direction at its destination point requires an additional three degrees. Thus, given a desired position and orientation of the hand, the angle of each joint, and consequently the arm configuration, is (in general) completely determined. However, many tasks require the ability to choose an appropriate position of the arm segments while still achieving proper hand positioning, in order to "reach around" objects or avoid collisions. This requires additional redundant degrees of freedom besides the basic six.

In the case of the human arm, a given hand position can be obtained while still allowing the location of the elbow to be changed to adapt to the working environment. The more redundant joints there are, the more adaptable the arm will be, but the problem of controlling the arm also becomes considerably more complex with each additional joint. The arms of the ETL robot described here, shown in Figure 1, are modelled after the human arm, with three degrees of freedom in the shoulder as well as in the wrist, allowing arbitrary positioning of the elbow.

Mechanical Design

The mass of the arm is a significant factor affecting its performance. Low arm weight increases its payload capacity and permits a reduction in the complexity of the control equations. [4] In order to minimize the arm mass, the joint actuators are removed from the arm. Torque is transmitted to each joint by a pair of cables that pull the joint in opposite directions. The difference between the tensions of the pair determines the net torque applied to the joint. The cables are kept in tension to eliminate play (backlash) in the joint and to accommodate variations in cable length caused by changes in the arm configuration. The stainless steel cables are led to each joint by guide pulleys. The joint actuators are mounted in the support

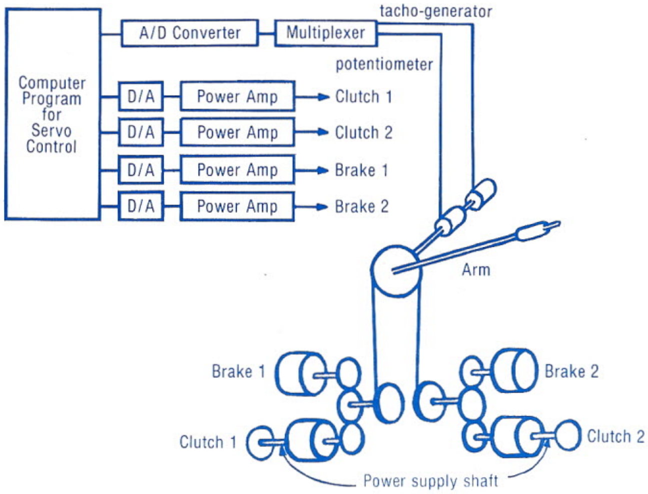

Figure 3. Diagram of the cable drive servomechanism for a typical joint. Each end of the cable requires both a clutch and a brake to provide the tension determined by the computer. The program reads the position and velocity of each joint through a multiplexed analog to digital converter.

structure behind the manipulators. [5]

The seven degrees of freedom are: (Figure 2(a)) shoulder azimuth and elevation, upper-arm rotation, elbow angle, forearm rotation and two orthogonal wrist pivots. The revolute joints of the shoulder azimuth and the forearm and upper-arm segments are accomplished by pulleys that translate the cable tension into a direction tangent to the arm's circumference (Figure 2(b)). Ball bearings are used in each joint. To minimize arm weight, the bearings in the lower two revolute joints consist of balls packed into circular grooves cut directly into the arm. Potentiometers and analog tachometers (DC generating) are directly coupled to the joint shafts to measure the angle and angular velocity of each joint. Both the upper-arm and forearm segments are 45cm in length.

The hand (Figure 2(c)) has three fingers, allowing stable grasping of an object with three contact points. It has two degrees of freedom — fingers F1 and F2 move together, and finger F3 is operated independently, retracting out of the way when opened. Potentiometers are used to measure the opening of fingers F1 and F2 and the position of finger F3.

A diagram of the servo drive system of a typical joint is shown in Figure 3. Continuous torque magnetic clutches were chosen as the joint actuators to supply tension in the cables. Instead of requiring a servo motor for each of the sixteen drive cables in an arm, a single powerful motor is used as a torque source for the entire manipulator, and is coupled to the input shaft of each clutch by timing belts. Under computer control, the clutch couples the desired amount of torque to its output shaft, which is in turn coupled to the cable drive pulley by gears. Each cable also has a magnetic brake to provide static torque to hold the

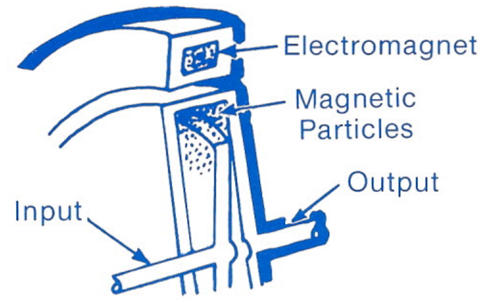

Figure 4. A magnetic powder clutch produces a torque proportional to its input current. The coupling is caused by the polarization of magnetic particles induced by the excitation field.

arm or to apply a controlled braking torque. Sixteen such driving pairs are used, two for each of the seven joints and one for each finger closing mode (finger opening is automatic upon release of closing tension).

Over its linear operating region, the amount of torque transmitted by a magnetic powder clutch is in direct proportion to the current through its electromagnet winding. The magnetic field produced by the current polarizes magnetic particles in the coupling medium, causing increased viscosity or friction between the coupling surfaces. (See Figure 4.) The amount of torque that can be transmitted is much greater than can be produced by a DC servo motor of similar size. Moreover, since the excitation current is considerably less than that required by a comparable servo motor, the power requirements of the servo output amplifiers are correspondingly reduced. The brakes work in a similar manner, but the input is coupled to a static shaft instead of to the motive power supply.

The servo amplifiers are designed to produce an output current proportional to the input voltage, which is set by the computer's digital to analog converter port.* When the computer is driving a joint in one direction, the other drive cable for the joint is set to a constant minimum tension to prevent backlash caused by slack in the cable. The maximum driving torque for each joint, together with its range of motion, is shown in Table 1.

Design of the Servo Control Program

To effectively accomplish force-related tasks, the servo control program must be able to accurately control the direction and magnitude of forces applied by the arm to

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**Editor's note: Methods of constructing a controlled-current servo amplifier may be found in most references on operational amplifier design. An exciting development in the design of switched-mode power converters suitable for servo applications will be presented in the next issue of ROBOTICS AGE.*

Joint	Maximum torque [Kg•cm]	Reach
R_1	200	180°
P_1	200	140°
R_2	150	180°
P_2	200	140°
R_3	46	180°
P_3	27	90°
P_4	27	90°
F_1, F_2	13 Kg	10 cm
F_3	24 Kg	8 cm

Table 1. Maximum torques (or forces) of the arm joints, with ranges of movement. [4] [*The kg-cm units for torque refer to kg weights, not masses. —ed.*]

Model	Language	Computation time
Matrix Model	Fortran	7.9 sec
Bejczy	Fortran	0.0025 sec
Walker	Fortran	0.0335 sec
Walker	Floating Point Assembler	0.0033 sec

Table 2. Times needed to compute joint torques, as implemented on a DEC PDP-11/45 computer using the methods shown. [7]

objects in the workspace. This control must be exercised in addition to the program's computation of the joint torques necessary to accomplish the desired arm movement. Much of the difficulty in these processes arises from the need to transform vectors from the workspace coordinate system into the system defined by the joints of the manipulator. For example, just as there is a correspondence between a desired end-effector location and orientation in the workspace and a particular set of joint angles, (assuming, for the moment, a six-degree of freedom manipulator) there are similar correspondences between velocity and force vectors in workspace coordinates and angular velocity and torque vectors for the joints.

The difficulty is further increased by the fact that the dynamic behavior of the arm is quite complex. Motion in one joint of the arm can cause "inertial" forces (centrifugal and Coriolis force) in other segments of the arm, and, for a force-controlled arm, appropriate torques must be applied to the joints to counter the effects of these induced forces. Changes in the joint angles cause changes to the moments of inertia (angular inertia) at other joints, as well as to the torques needed to counteract gravity. The joint torques necessary to move a force-controlled arm along a desired trajectory in the workspace can only be computed from a detailed "model" representing the Newtonian equations of motion of the arm.

The most convenient method of describing the problem is in the Lagrangian formulation of Newtonian mechanics.* The resulting equations are expressed in terms of matrix operations, which, although mathematically very concise, require considerable computation time to apply. An approach used in early force-controlled manipulator systems was to compute "torque curves" which predicted the necessary torque for each joint, as a function of the elapsed time during the movement. The computation was performed before the start of the motion, and the servo program used the "planned" curves to simplify its real-time control of the arm. [6]

Unfortunately, such a method precludes the ability to compute joint torques in response to forces on the arm resulting from its interaction with objects in the workspace — the same force control ability mentioned above. Because of the complexity of the arm's dynamic behavior, the computation of joint torques in real-time has been considered by some to be impossible with conventional computers. However, recent improvements both in joint torque calculation algorithms and in arithmetic hardware elements have now made this capability attainable. Bejczy developed an approximation method in vector representation which can determine joint torques very quickly. A vector method by Walker uses a recursive algorithm to derive torques without redundant computation. [7] As shown in Table 2, with these methods we can now compute joint torques from about 200 to 300 times faster than the traditional matrix model.

Powerful arithmetic elements, such as a 16 bit by 16 bit LSI multiplier chip with 200 nanosecond execution time, have also become available. Using these devices, special purpose processors could be developed for performing fast vector operations, such as scalar (dot) product or vector (cross) product, improving the execution times of the above methods by a factor of ten. These considerations show that the calculations required for sophisticated real-time control of the forces applied by the arm in a Cartesian workspace coordinate system could easily be performed in less than 10 milliseconds — an adequate loop cycle time for most sampled servo systems.

A generalized servo system for force and motion control in Cartesian coordinates is shown in Figure 5. The task to be performed may be specified in a high-level robot programming language that describes the desired behavior

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**Editor's note: A good introduction to the manipulator modelling problem can be found in reference* [9].

of the arm in the workspace (box at bottom). The execution of the task-specific program causes arm force and movement commands (expressed in the workspace coordinate system) to be given to the control module. The control module is task independent and, based on the commands and feedback describing the arm's position and velocity in the workspace, decides both what its acceleration should be and what force it should be applying to objects in the workspace. Since the force and acceleration are expressed in workspace coordinates, this module may be independent of the particular robot arm used, resulting in greater system generality.

The arm-dependent parameters are expressed in the coordinate transformation modules. One such module transforms the applied force specified by the controller into a set of joint torques (T_f) that should result in the desired force vector in the workspace. If an acceleration of the arm is specified, a second transformation computes the torques that should cause angular accelerations in the joints (T_a) to produce the desired movement in the workspace. Finally, the feedback from the arm's joint position and velocity sensors must be transformed into the corresponding position and velocity to the workspace.

Since the joint torques caused by the weight of the arm and the inertial forces induced by arm movement are most easily expressed in terms of the joint angles and motions, no transformation to workspace coordinates is necessary. A separate module computes torques that should cancel the effects of these forces (T_c), so that the arm acceleration transform can effectively ignore their effects. This simplifies that transform to (the equivalent of) a single matrix operation. The three sets of joint torques, T_a, T_f, T_c, are combined and used to determine appropriate control signals to the output amplifiers for the joints.

Due to various error sources and uncertainties in the arm's response to the control torques, the actual response measured by the feedback sensors (giving the position and velocity for each joint) may differ from that expected. On the next control cycle, any observed differences produce error terms which contribute to the next output commands. The control torques must be re-evaluated at a frequency determined by the mechanical response time of the particular arm used.*

Note that the diagram does not show a feedback signal that measures the actual force applied by the arm. Although pressure transducers capable of providing such

Editor's note: A good introductory reference to sampled servo loop design is "Discrete Time Systems", by J. A. Cadzon, Prentice Hall (1973).

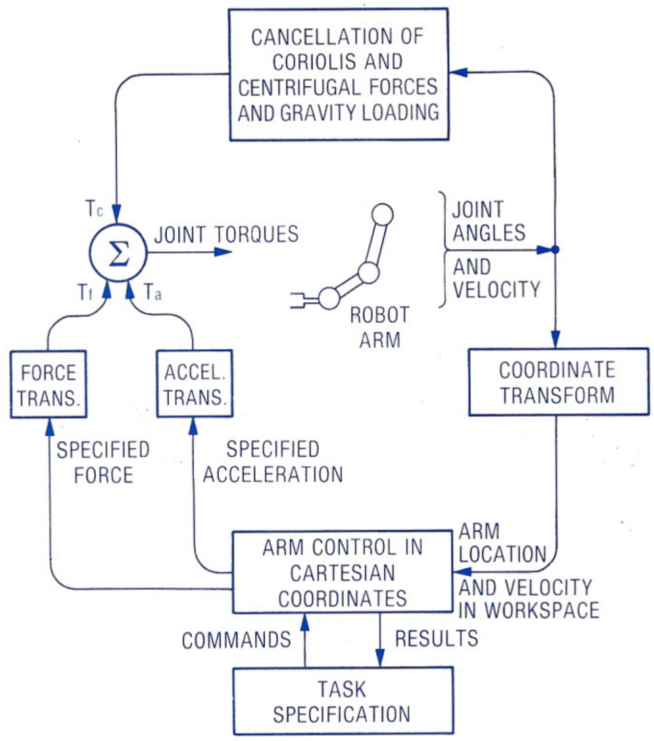
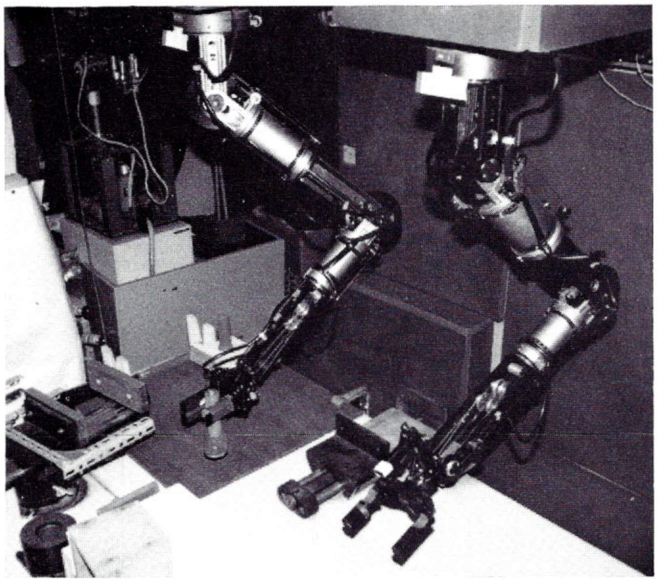


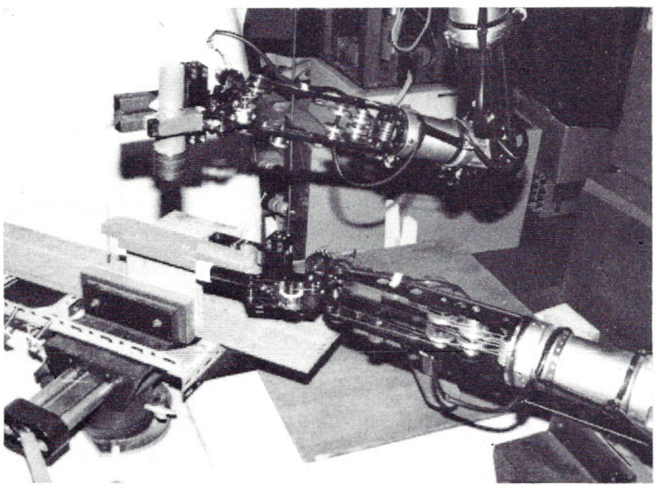
Figure 5. A generalized servo control loop for force control in Cartesian workspace coordinates. Advanced control algorithms allow forces and motion to be specified in the task domain and translated to arm joint torques in real-time.

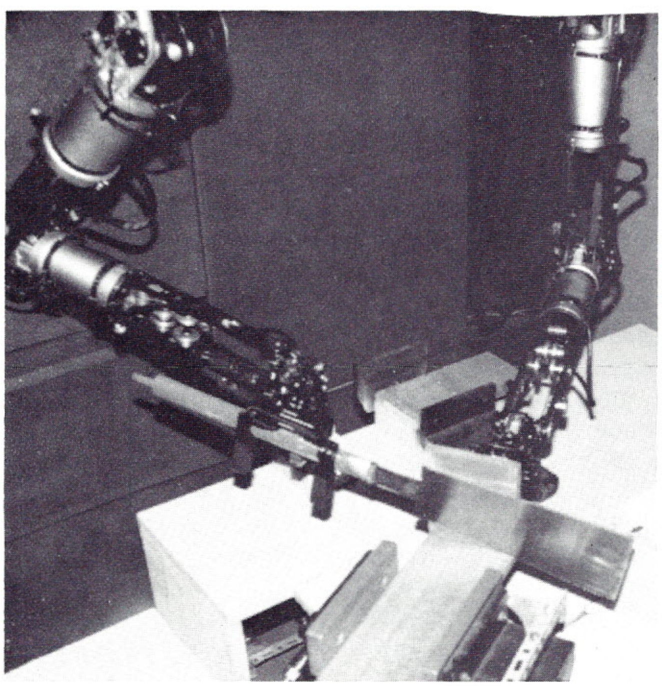
feedback are becoming available, [8] the methods of using such feedback in the generalized control system in Cartesian coordinates are still under development. In the present system, force control is still "open loop", that is, the torques T_f are those that *should* produce the applied force desired, instead of those determined from measured force feedback. Even so, the applied force can still be controlled to an accuracy of ± 100 grams (weight).

Results and Conclusions

Using a control system similar to the one described here, the dual manipulator system has been applied to several tasks requiring real-time control of applied forces as well as motion. These include turning a crank, boring a hole with a carpenter's brace and bit, sawing wood, driving nails with a hammer, and others. (See photos.) The extra degree of freedom in the arm movement plays a vital part in expanding the working range and making the motion smooth. In turning a crank, for example, the orientation of the elbow can be left unspecified, so that the elbow can be manually pushed to a different orientation without affecting the arm's functioning. The net force is always applied in the direction of turning, i.e., tangent to the crank's movement, which would be difficult to accomplish by position or motion control alone. Partially constrained motions are easily accomplished by directly controlling the torques of each joint.







The skills of an "intelligent" robot may be thought of as consisting of accumulated knowledge about how to perform particular tasks. This knowledge may be provided by a software description of the task procedure and the special techniques, or "virtual mechanisms", it requires. In general, the desired behavior is most easily expressed in terms of the motions and forces in the workspace coordinate system. To carry out the task requires real-time control of this behavior in the workspace frame by monitoring the actual response patterns. This capability is now possible, and the control system organization described here provides a generalized framework for achieving these results.

References for Part I:

[1] T. Goto, et al., "Precise Insert Operations by Tactile Controlled Robot", Proc. 4th Intenational Symposium on Industrial Robots (ISIR4), Tokyo (1974).

[2] J. L. Nevins, et al., "Computer Controlled Assembly", Scientific American, 238/2, February 1978.

[3] C. Rosen, et al., "Machine Intelligence Research Applied to Industrial Automation", 8th Report, SRI International, Menlo Park, CA, August 1978.

[4] K. Takase, "Skills of the Intelligent Robot", Proc. 6th International Joint Conference on Artificial Intelligence (IJCAI6), Tokyo (1979).

[5] K. Takase, et al., "The Design of an Articulated Manipulator with Torque Control Ability", Proc. ISIR4, Tokyo (1974).

[6] R. Paul, "Trajectory Control of a Computer Arm", Proc. IJCAI-71, London, September 1971.

[7] R. Paul, et al., "Advanced Industrial Robot Control Systems", First Report, Purdue University, West Lafayette, IN, May 1978.

[8] B. Shimano, "Force Control—Exploratory Study of Computer Integrated Assembly Systems", T. O. Binford, et al, Stanford AI Laboratory Memo 285.4, June, 1977.

[9] Berthold K. P. Horn, "Kinematics, Statics, and Dynamics of Two-Dimensional Manipulators", in *Artificial Intelligence: An MIT Perspective*, Winston and Brown, eds., MIT Press Cambridge, MA (1979).

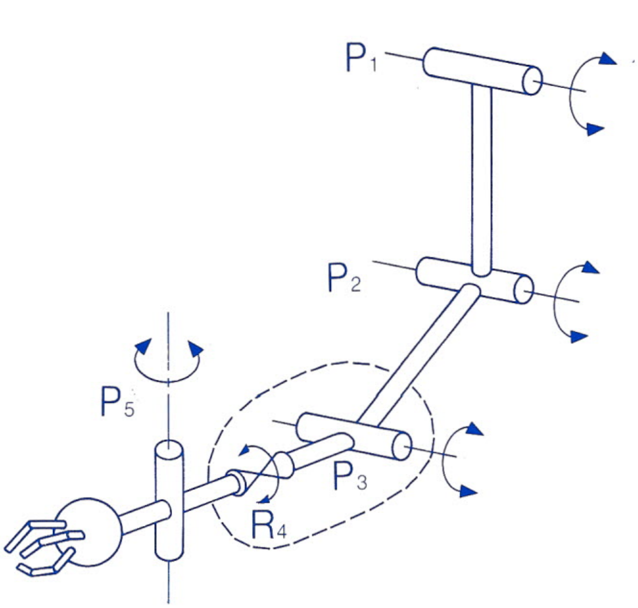


Figure 2. Schematic representation of the five degrees of freedom of the manipulator arm. Pivotal joint P_3 and rotational joint R_4 are realized by a single differential gear unit. (See Figure 3).

(continued from page 31)

mechanical characteristics of the human hand may be reproduced. Foremost among these is the ability to operate each finger joint independently, controlling either its position or its applied force. A computer-controlled manipulator featuring a human-like artificial hand with such a capability has been developed at ETL. Figure 1 shows a photograph of the end-effector.

Mechanical Design

Since the experiments to be performed deal primarily with the manipulative capabilities of the anthropomorphic hand, a relatively limited arm subsystem is sufficient to accomplish positioning of the hand. The five degrees of freedom are shown schematically in Figure 2. Two joints, shoulder elevation and elbow angle, are used to position the wrist within a plane operating envelope. The three wrist joints determine the orientation of the hand.

The elevation and rotation of the wrist relative to the forearm are determined by the action of a single differential joint, illustrated in Figure 3. The angle of each of the operating gears (L and R) is controlled independently, and the differential gear (D) is meshed with both. Moving the operating gears in the same direction changes the elevation of the wrist segment, whereas moving them in opposite directions rotates the wrist. Wrist azimuth is controlled by a separate joint in the wrist segment, which also carries the end-effector out of the operating plane of the arm.

The fingers are designed to approximate the flexbility of their human counterparts. Three fingers were provided to permit the stable grasping of objects with three contact points, and correspond roughly to the human thumb, index finger, and middle finger, as shown in Figure 4. Fingers 2 and 3 each have three joints that bend toward or away from the palm, but the thumb has only two. Each finger has an additional joint close to its base that can move it from side (lateral abduction and adduction), thus tilting the bending plane of the outer joints relative to that of the base joint, maximizing the operating envelope of the finger.

Each finger segment is made of a 17mm diameter brass tube with a fixed pulley at its base end whose axis is also the hinge with the previous segment. The pulley is turned by a pair of stranded stainless-steel cables, each of which is guided to the joint through a coil-like flexible hose, eliminating the need for guide pulleys in the nearer joints.

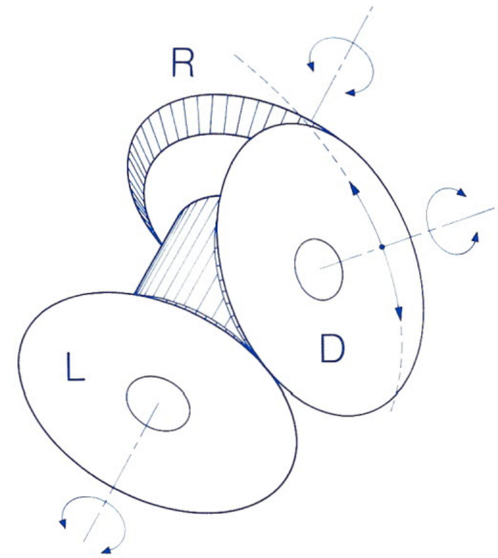


Figure 3. Wrist rotation and elevation are accomplished by the combined action of gears L and R, which position the differential gear D.

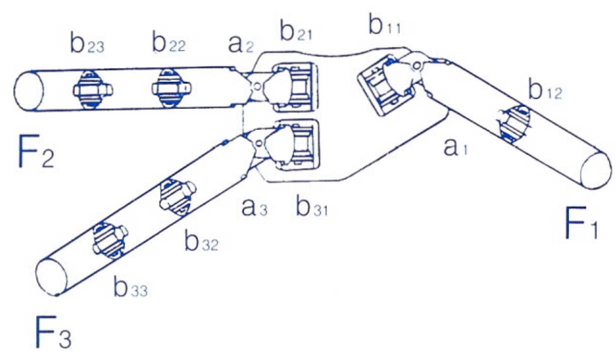


Figure 4. Degrees of freedom of the hand. Bending joints (b) flex the finger for grasping. Abduction/adduction joints (a) cause sideways movement of the finger.

ETL Drawing

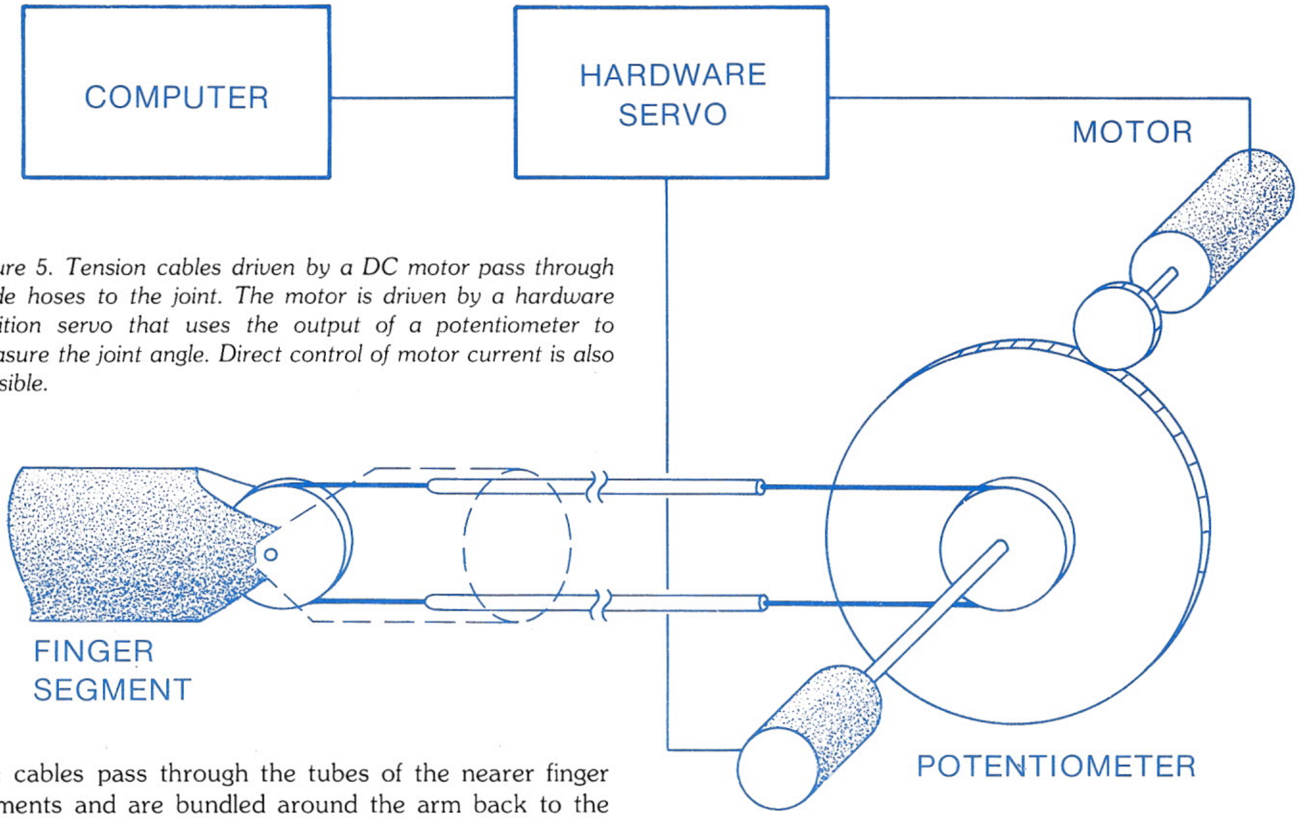


Figure 5. Tension cables driven by a DC motor pass through guide hoses to the joint. The motor is driven by a hardware position servo that uses the output of a potentiometer to measure the joint angle. Direct control of motor current is also possible.

The cables pass through the tubes of the nearer finger segments and are bundled around the arm back to the trunk. The entire hand only weighs 240 grams, and it can hold a 500 gram object. Rubber fingertips (missing in some of the photographs) are added to help prevent slippage while grasping. [1]

A schematic diagram of the drive system is shown in Figure 5. Each joint actuator, located in the trunk, consists of a single drive pulley geared to a DC motor. Although the single drive configuration does introduce some backlash, it is kept within acceptable limits by mechanically adjusting the net tension of each cable pair. The bending angle of each joint is measured by a potentiometer, and joint torque is indirectly determined from the motor current. For this purpose it is assumed that the friction between the cable and the wall of the guide hose is approximately constant, since only very slow cable movements are needed to deflect the joint. Cable drive is also used in the wrist joints, but the shoulder and elbow are driven by motors geared directly to the joint.

Freedom		Motion	Angular Range [deg.]	Speed [deg./sec.]	Power [w]
Arm	P_1	Shoulder Swing	-45—45	45	30
	P_2	Elbow Extension	0—90	45	10
	P_3, R_4(L,R)	Wrist (el., rot.)	-180—180	45	2.2
	P_5	Wrist Azimuth	-60—60	90	2.2
F_1	b_{12}	Bend, Extend	-45—90	600	
	b_{11}		-45—45	500	
	a_1	Abduct, Adduct	-60—60	500	2.2
F_2 (F_3)	b_{23}	Bend, Extend	-45—90	600	
	b_{22}		-45—90	600	
	b_{21}		-45—45	500	
	a_2	Abduct, Adduct	-60—45	500	

Table 1. Physical specifications of the maniplator and hand. [1]

Mechanical and electrical specifications for each joint are shown in Table 1. Note that the outer bending joints of the fingers are capable of bending 45° outward as well as 90° inward. This gives the hand an ability not only to grasp an object by closing around it from the outside, but to grasp hollow objects by pressing outward from the inside as well.

Control of the Fingers

Due to the large number of controllable joints in the system, (five arm joints and eleven finger joints) the computational overhead of a software servo system would be prohibitive. Therefore, each joint is controlled by a hardware servo loop. A feature of the servo design used for the finger joints is its ability to switch a joint between position and torque control. This feature makes it possible

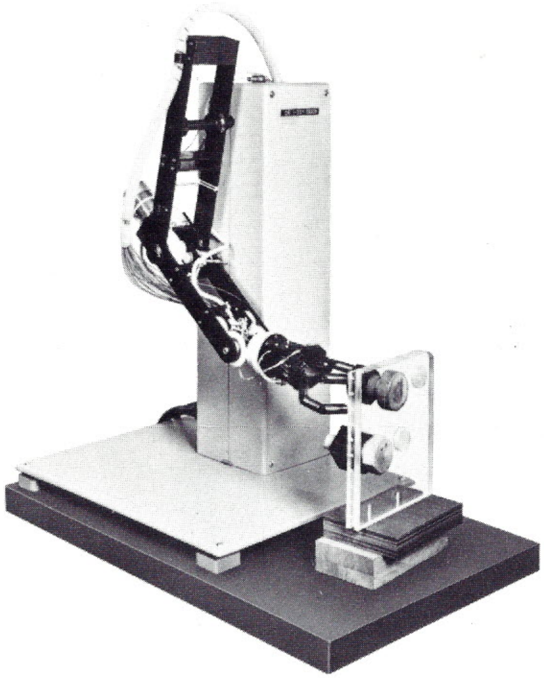
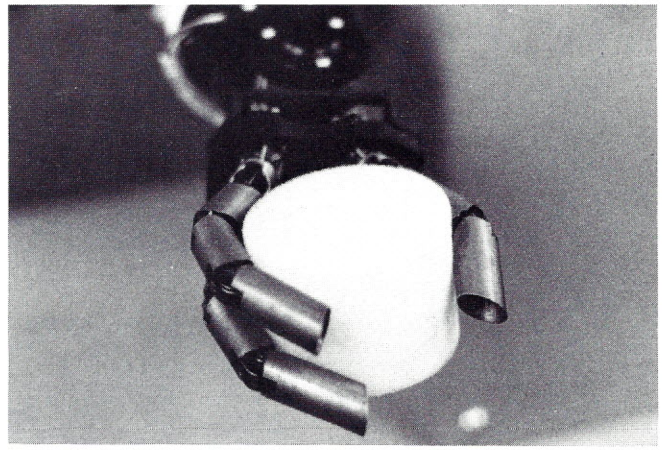


Photo of the anthropomorphic manipulator system, shown tightening a nut on a threaded shaft. The flexible finger structure allows programmable automation of a variety of manual tasks.

to keep the grasping force constant even when the fingers are changing position. For example, one finger may be explicitly moved using position control while the others follow passively, applying the desired force.

The methods of determining the position control inputs to the finger joints are very similar to those used in manipulator control. In one approach, a sequence of "set points" for each joint are taught to the controller by moving the finger in a manual control mode. At regular intervals during the motion, the value of the joint angle for each of the joints is measured and stored in a table. Later, smooth automatic position control in the interval between the set points is provided by interpolating uniformly between adjacent values in the table for each joint, reproducing the original movement.

The second approach involves computing the values of the joint angles required to position the fingertip at a desired location and orientation.[3] Since it has only four degrees of freedom, two of which determine finger bending angles that lie in the same plane, only the angle of the tip segment in the bending plane of the outer two joints can be controlled. Nonetheless, this makes it possible for the hand to roll the fingertip while still maintaining contact with a grasped object and not slipping. In cases where a particular grasping angle is not specified, the transformation from the fingertip location (in a Cartesian frame attached to the palm) to a set of joint angles is simplified by assuming that the bending angles of the two outer joints are equal. This effectively reduces the number of degrees of freedom in the finger to three and thus completely determines the transformation. [2]



Performance on Simple Manual Tasks

The advantages of having selectable position or torque control were demonstrated by having the fingers shift a cylindrical bar from side to side while holding it vertical. This was done while holding the hand still by controlling the bending joint at the base of the finger, keeping the other joint angles constant to maintain the original grasping positions. While varying the base angle of one finger, the base joint of the opposing finger was held at constant torque and allowed to follow the movement. As a result, bars of various diameters were moved smoothly without dropping or crushing them. Special circuitry in the hardware servo loop facilitates smooth transitions between position and torque control even in the presence of tracking error caused by gain limitations.[2]

Several other tasks have been performed as well. By lifting and repositioning one finger while the other pair maintains a grasp, the skills of twirling a baton and turning a sphere while holding it have been demonstrated. In both cases the hand location remained fixed while the rotation was accomplished by finger movement alone. Capabilities such as these make this system a successful step toward the further automation of manual tasks. Future research will address more complex tasks, such as tying a knot, fastening buttons, and using chopsticks. The integration of tactile and force sensors into the system is also being considered.

References

[1] Okada, T. and S. Tsuchiya, "On a Versatile Finger System", Proc. ISIR7, Tokyo, 1977.

[2] Okada, T., "Object-Handling System for Manual Industry", IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-9, No. 2, February 1979.

[3] D. L. Pieper, "The Kinematics of Manipulators under Computer Control", Stanford Artificial Intelligence Project Report No. 72, Stanford University, CA (1968).

Report from IJCAI6 Tokyo – 1979

第6回人工

Every two years, researchers in the field of Artificial Intelligence (AI) travel from around the world to the International Joint Conference on AI, or IJCAI.* Since the first IJCAI, held in Washington, DC, in 1969, alternate conferences have been located outside of the US. This year's conference was held in Tokyo, Japan, in keeping with this policy. Although the high cost of travel greatly reduced the number of North American attendees, the choice of Tokyo appropriately recognized the growing contribution to the field made by Japanese AI researchers. Over 500 persons braved the sweltering humidity of the Japanese summer and the threat of typhoons to attend the conference, which was held in excellent (air-conditioned) facilities provided by the Japanese hosts.

Artificial Intelligence may be loosely defined as the study of the computational principles that underly human intelligence or "intelligent" behavior in general. Clearly, this definition is extremely broad, and the research encompassed by it addresses almost every aspect of human functioning — reasoning, sensory and motor skills, and even artistic and emotional expression. Because of this, IJCAI has grown to become many conferences in one. Technical papers are presented in a variety of sessions, each concerning a particular area of current research. With several sessions held simultaneously, participants may concentrate on their own specialty or "browse" through other topics for useful results. The latter approach can be quite rewarding, because techniques proven useful in one class of problems can frequently be applied to others, clearly suggesting that diverse capabilities may possess an underlying unity.

With more than two hundred technical papers presented at the conference, it would be impossible to give an adequate survey of the results reported. Instead we will give a brief description of some of the major research areas within AI and in some cases comment on the state of the art as exemplified by current systems. The intent is to give the reader a very brief survey of the field as well as outlining the kinds of topics addressed by papers in the proceedings.

In addition to the contributed papers, several prominent researchers were invited to discuss the issues underlying current study in their particular area and to speculate on the nature of future developments. The invited lectures provide a valuable means of putting the field in perspective, and some of them will be summarized below.

Vision

Computer vision remains one of the central topics of AI research, as evidenced by the eight sessions devoted to it at IJCAI6. Basically, the problem is that of translating an array of light intensities representing a digitized image into

IJCAI is often pronounced "itch-kye" (rhymes with "eye").

Keith Price
Image Processing Institute
University of Southern California
Los Angeles, CA
and
Alan M. Thompson
Robotics Age Magazine

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useful information about objects or features in the environment.* The papers dealt with all aspects of vision: *Low-level* vision refers to the process of finding the edges of objects or lines in the image array and also to extracting shape or texture information. From these results *high-level* procedures interpret the scene in terms of known objects. Intermediate processes may serve special functions such as locating individual objects or determining their motion. Recently the term *image understanding* has been applied to the entire process: low-level feature detection, middle-level description procedures, and high-level analysis procedures.

Although the general purpose, practical vision system is still a distant goal, progress was reported in several areas. Of particular significance for robot vision systems is the development of techniques and special hardware that provide basic vision functions at speeds fast enough for use in robotics and real-time control. One such system, developed in Japan, is employed in a driverless "intelligent" car that can drive on normal roads at speeds up to 30 Km/h, automatically avoiding stationary obstacles or stopping if necessary. [1] Other Japanese systems under development are capable of finding a path around people in a hallway [2] and computing the relative distances and velocities of cars [3] in real time so that a robot car can operate in traffic.

The *Computers and Thought* Award is presented at each IJCAI to a young researcher who has made an outstanding contribution to the field. The award is sponsored by the authors of an AI book of that title, [4] and the recipient is invited to present a special lecture at the conference. This year the honor went to Dr. David Marr of MIT for his notable work in computer vision, which is based on a thorough background study of psychophysical visual functioning. In the text of his lecture, Dr. Marr presented a systematic approach to extracting shape information from images and argued that these processes should preceed the interpretation of the image, extracting the most complete shape description before attempting to recognize objects. Unfortunately, due to illness, Dr. Marr could not attend, and the lecture was presented by his colleague, Dr. Shimon Ullman.

Problem Solving, Reasoning and Knowledge Representation

The notion of *problem solving* covers a broad area of machine intelligence research — indeed, every successful system in some way "solves" a problem. However, this term is normally used to refer to systems that apply logic, reasoning, and knowledge to solving a general category of

**See the article "An Introduction to Robot Vision" in the Summer/Fall 1979 issue of ROBOTICS AGE (Vol. 1, no. 1).*

Members of the IJCAI Executive Committee. Seated left to right are: first row—Bruce Buchanan, Stanford University, Woody Bledsoe, University of Texas at Austin, and in the second row—Raj Reddy, Carnegie-Mellon University, Kokichi Tanaka, Osaka University, and Herbert Simon, Carnegie-Mellon.

problems explicitly stated in words (or capable of being so expressed). Examples of this *symbolic* reasoning are textbook problems in mathematical logic, or most "What", "Why", or "How" questions.

At IJCAI, nine sessions were devoted to papers related to reasoning of this kind, most of them describing techniques for manipulating symbolic representations of the problem and the available facts. These included sessions on programs that seek proofs to mathematical theorems, those that answer questions about facts represented as symbolic expressions in a database, and methods of using statistical evidence or numerical estimates of the "credibility" of assertions to infer plausible answers from inconclusive facts. Other programs in this category are capable of planning a sequence of actions that accomplishes a goal, given some initial condition.

One of the keys to computer reasoning is the ability of a program to limit the alternatives it must consider when seeking the solution to a problem to those that are most likely to succeed. Just as it would be physically impossible to enumerate all possible board positions ten moves ahead in a chess game, it is impractical to consider, for example, all different ways of proving a mathematical theorem. The process of effectively limiting the number of candidate solutions a program must evaluate is referred to as *heuristic search*, and is common to many AI systems.*

One traditional approach to search control is to program special procedures that apply to problems in a particular domain or of a particular kind (such as measuring the desirability of a particular board situation in chess). A growing trend, however, emphasized by a number of papers at the conference, is to use methods based on analyzing the *structure* of a problem, when the problem is expressed in a particular form.** An important advantage of this approach is that the methods developed can be applied to a variety of problems — if a new class of problems can be expressed in a given notation, then in many cases a program designed to operate on that notation will be able to solve the new problems without alteration.

This approach can also be extended to give a program the capability of using explicitly stated advice about how to solve problems. Instead of being controlled by hand-coded procedures, the program's behavior may be determined (or influenced) by applicable advice put into a database by the user as part of the system's "knowledge" about the problem domain. In many cases the advice may be expressed in the same language used to represent the problem description and the available facts. This introduces the possibility of making the rules governing the program's behavior themselves accessible for consideration by the reasoning process, thereby providing a framework for introspection and machine learning.

Thus, the problem of search efficiency has become closely related to that of choosing effective representations. This is one reason why the design of representations has in itself become an important topic in AI, with five sessions devoted to it at IJCAI6. The generality of a particular representation scheme cannot be considered apart from the methods necessary for its effective use. English and the other natural languages can be used to express most of human knowledge, but processing sentences to extract information is a major AI problem in itself. By contrast, algebraic expressions are relatively easy to reduce but are limited to representing numeric problems.

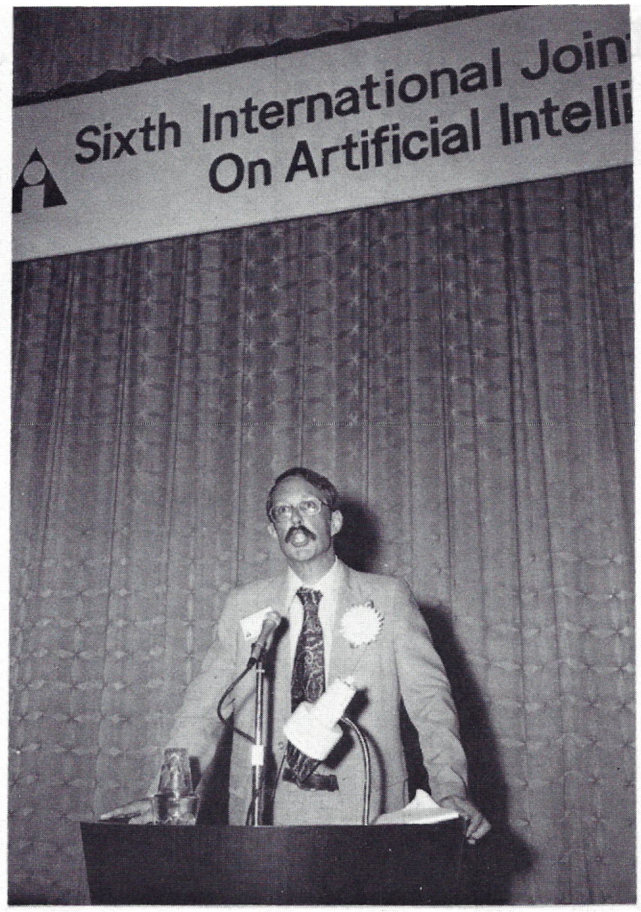
It is commonly accepted that generality and efficiency are conflicting goals and that practical systems for symbolic reasoning must employ representations that are

---

A good introduction to the issue of search efficiency may be found in "Artificial Intelligence", by Patrick H. Winston, which is reviewed in this issue.

**An example of what is meant by the representation of a problem is provided by the familiar "word problem" of high-school algebra. Once a problem is translated from English sentences to its representation in algebraic formulae, its solution can be obtained by standard procedures. Similarly, problems and facts can be explicitly represented inside a computer by an appropriate data structure, instead of being implicit in the program itself.*

IJCAI6 Program Chairman Bruce Buchanan had the difficult tasks of managing the selection of over 200 papers from the many hundreds submitted and then organizing them into sessions for presentation.



deigned for a particular type of problem. However, most of the papers in the sessions on representation presented schemes designed for effective use on a broad class of problems. Indeed, one paper effectively argued that in some cases programs capable of an extensive deductive analysis of a problem when it is expressed in a general representation can find solutions far more efficiently than programs written specifically for solving the same problem.[5]

An invited lecture by Dr. Earl Sacerdoti of Stanford Research Institute addressed the issue of *plan generation* — the problem of determining a sequence of actions that will achieve desired goals. This capability is essential for intelligent robots that must choose an appropriate course of action based on observed conditions. The lecture provided a brief survey of current methods which characterized the essential elements of successful planning systems. In addition, new lines of research were recommended for achieving improved planning performance through the effective combination of current techniques.

Understanding Natural Language

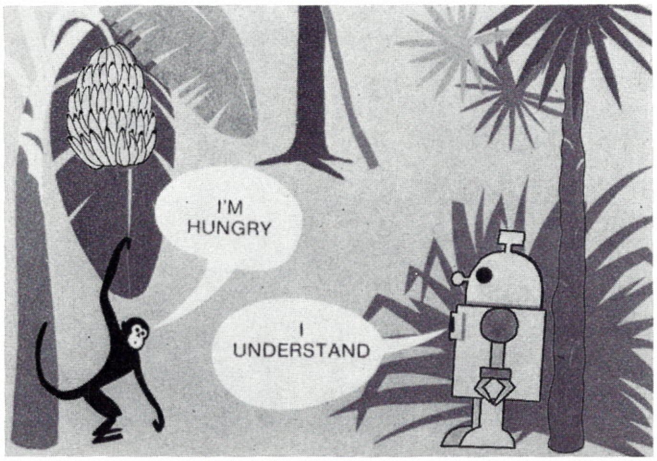
The ability to interpret the meaning of sentences in any human language requires considerable knowledge about grammar, word definitions, and the context of the utterance. AI research in this area combines elements of linguistics with problem solving techniques directed toward achieving the goal of more *natural* human-machine interaction. The problems faced by researchers in this specialty are quite similar to those found in the other types of symbolic reasoning, and, because of these similarities, the development of programs that understand Natural Language (NL) has closely paralleled that of problem solvers.

In particular, much current research effort is directed towards designing effective representations for the world knowledge that a general-purpose program needs to extract the most information from input sentences. Papers presented in the eight NL sessions at IJCAI6 were representative of the diverse approaches being studied. Individual sessions concentrated on the problems of NL processing particular to following dialog and answering questions.

The complexity of the problem of understanding NL utterances was illustrated quite effectively by Dr. Barbara Grosz of SRI. In her invited lecture, Dr. Grosz presented a variation of the classic "monkey and bananas" problem popular in early automatic problem solving research. In the original problem, a bunch of bananas are hanging out of the reach of a hungry monkey, and the monkey must invent a plan to reach the bananas by moving a nearby box underneath them so he can climb up. In her variation of the problem, Dr. Grosz introduced a second monkey, who knows that it is possible to use a long stick to knock down bananas from a tree. The response of the wiser monkey to the younger's "I'm hungry!" demonstrated that effective communication requires an understanding of the objectives of the parties involved and presupposes a good deal of common-sense reasoning. (See figures.) By her example, the limitations of many current NL systems were made abundantly clear, thereby, suggesting appropriate directions for future research.

Robotics

Robotics may be considered just a small part of AI, if by robotics we mean only the problem of intelligently controlling mechanical hardware. Alternatively, the two may be considered synonymous, since every aspect of AI research



A variation of the classic "Monkey and Bananas" problem was used by Barbara Grosz of SRI to illustrate the difficulties of natural language communication. The response of the older monkey indicates an understanding of the motive of the younger's exclamation as well as a desire to help. It also assumes that the younger monkey will understand the plan for obtaining the food. By contrast, the response of the robot indicates only a superficial understanding of the meaning of the utterance, which is a limitation typical of many current systems.

may be aplied to future intelligent robots. When referring to robotics, however, AI researchers typically mean those problems that are *unique* to the effective automatic control of electromechanical devices. Other talents, such as reasoning or sensory understanding, may be employed by many computer systems besides mechanical robots. Only two of the sixty conference sessions contained papers on robotics in this restricted sense.

Several robot systems were described in the sessions on Computer Vision, including the impressive driverless car mentioned earlier [1] and a computer-controlled "cart" developed at Stanford University. The latter robot employs a novel method of measuring the distance to objects by sliding its single TV camera sideways along a track to obtain multiple stereo views. Range is obtained by measuring the parallax shift of an image feature in nine images taken at different positions along the track. After moving forward about one meter, the mapping process is repeated, and the robot measures the actual distance traveled by finding its movement relative to surrounding objects. Vision is the system's only means of navigation. The cart is connected by radio link to its controlling computer, and the stereo vision processing takes about ten minutes of elapsed time on the remote time-shared computer, which also finds a safe path around obstacles.

Another research robot described at the conference is the HILARE system, developed at the CNRS Laboratory in Toulouse, France. HILARE serves as a testbed for addressing problems of perception, learning, planning, and communication. On-board microcomputers can communicate via radio link to stationary minis and a large remote time-shared system. Most control problems are handled on-board—communication with the other controllers is required when new instructions or advice are needed. The robot has a TV camera and 10 close-range ultrasonic proximity sensors, as well as a laser rangefinder. Other features are a telemetry laser and an infrared triangulation system for navigation.

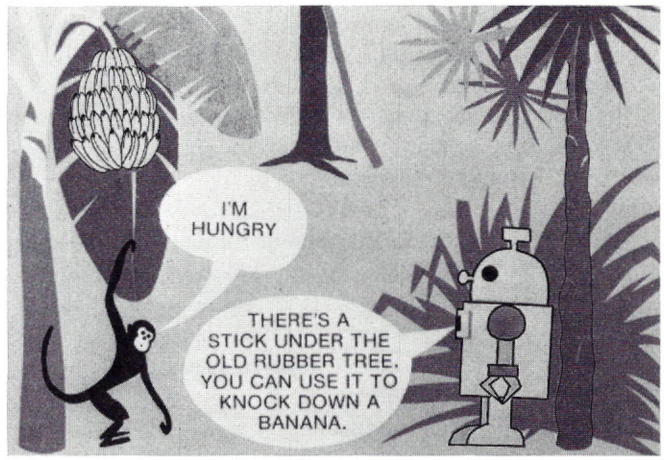
Two anthropomorphic robot manipulators developed at Japan's Electrotechnical Laboratory were highlights of the conference. All present were entranced by the human-like movements of the robots in films of their performance of difficult manual tasks. The dual force-controlled manipulator system of Dr. Kunikatsu Takase was shown doing carpentry jobs requiring cooperation between the arms, such as sawing wood and driving nails, and turning a crank. The structure of Dr. Tokuji Okada's three-fingered robot hand closely resembles that of its human archetype, and it was shown rotating a sphere *while holding it* and also slowly twirling a stick — performing each task by finger movement alone, with a human-like dexterity that many found somewhat uncanny.*

Computer Architecture

AI has always contributed to the area of computer hardware and software design, most notably in the area of time-sharing systems. The current developments, as reported at IJCAI6, are in the areas of parallel control structures, as applied to AI systems, and special computers to directly run AI programming languages. The most important computer language for AI research is called LISP (derived from the term *List Processing)* which

*Technical papers describing these robots have been adapted by ROBOTICS AGE as material for the article "Robotics Research in Japan" elsewhere in this issue.

Even if the hungry monkey makes its intentions more explicit, the crucial point of recognizing the purpose of its inquiry may still be missed by a mechanical system that provides only literal answers. As shown in the bottom frame, the ideal robot would recognize the true intent of the utterance and use its knowledge to aid its questioner in attaining those goals. To do so requires a reasoning capability far beyond interpreting merely the superficial meaning of a sentence.



was originally developed in the early 1960's to provide the symbolic data structures necessary for effective knowledge representation and problem solving.

The basic data structure in LISP has two components, the head and tail of the list, and all data and program statements are stored in this form. Since the instruction sets of most computers are designed for numeric applications, the basic list processing operations typically require numerous machine instructions, with a concomitant loss of efficiency in LISP programs. The decreasing price of computer circuit elements has made it possible to build machines that directly execute basic LISP operations in hardware. This has led to the development of a variety of LISP machines, especially in Japan. [7,8,9]

Each of the various machines are designed to implement, in hardware or microcode, various time-consuming operations which are common to all LISP systems. Necessary operations include access to particular structures to locate the actual value of locates all elements of a particular structures to locate the actual value of some variable and the process of *garbage collection*, which locates all elements of a particular data type (list cells, for example) that were previously part of an active data structure but are now no longer referenced. The NK3 machine [8] has been developed around the Interdata 8/32 and is based on a micro-programmable computer with special microcode which aids in writing LISP systems. The machine described by Taki [9] is intended to be a personal computer and is used in conjunction with a Digital Equipment Corporation LSI-11 microcomputer. Another special harware design for symbolic processing is the FLATS system [10]. This system is not designed specially to execute LISP but is intended to provide the mechanisms necessary to implement the data structures used by LISP and other symbolic languages. This machine is still in the design and implementation stages.

Automatic Programming

The idea of converting natural language descriptions directly into computer programs has always been a major goal of AI research. In recent years this field has grown to the extent that much of the research in automatic programming is no longer considered to be a part of AI but is a separate field of its own. At this meeting there were three sessions devoted to the area of program synthesis. Like other subareas of AI, work in automatic programming must address the fundamental issues of knowledge representation, problem solving, and natural language understanding. Thus, there is considerable overlap between this and other specialties.

To make the problem more tractable, the goals of current program synthesis work have been scaled down from taking the initial specification in free-form English to requiring the problem specification to be in a more restricted syntax not unlike current programming languages.* Many systems are designed to interact extensively with a human programmer to develop the desired program a step at a time. A closely related approach is to have the computer analyze a human-supplied program for correctness. If the system can "understand" the code it may be able to find a proof that the program will or will not work.

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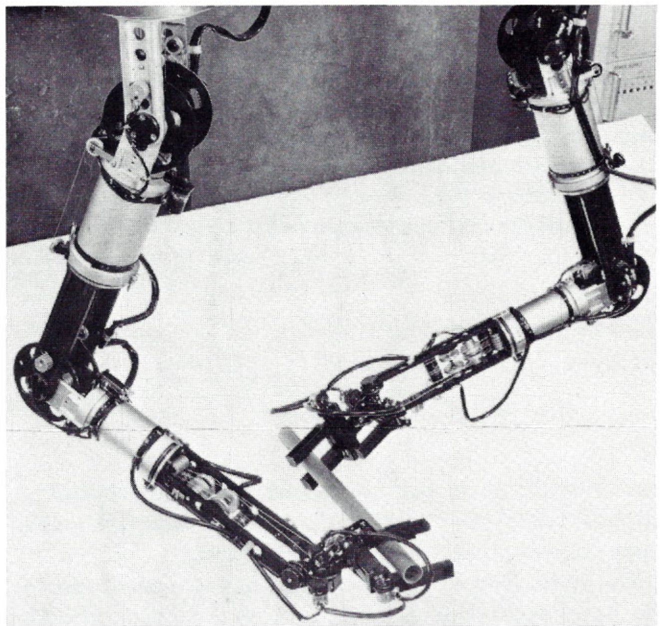
* Indeed, the term automatic programming has had many different meanings over the years and was originally applied to the use of assemblers instead of manually writing programs in numeric machine code!

Robotics Research at Japan's Electrotechnical Laboratory was featured in an invited lecture by Kunikatsu Takase. This robot manipulator system was shown in a film performing carpentry tasks using a saw, a drill, and a hammer.



Game Playing and Other Topics. . .

Many other subjects were addressed by sessions at the conference—researchers discussed computer systems that learn new behavior, create art, model human psychology, and advise experts on medical treatment or geological exploration, just to name a few. A satellite communications link with the U.S. was provided so that some of the programs could be demonstrated at the conference. Among these was BKG, the backgammon program developed by Prof. Hans Berliner of Carnegie-Mellon University. This program recently won the International Backgammon Tournament by defeating the human champion in a closely-fought match.

At this conference a new award was established to recognize outstanding long term contributions to the field of AI. Bernard Meltzer, formerly of the University of Edinburgh AI Laboratory, has for many years been a leading force in AI research both as a researcher and editor of the major technical Journal in the field. In his invited lecture, Prof. Meltzer speculated on the nature of human language and its implications for the development of computer programs that understand it. His discussion revolved around the question of the form of the internal language of human thought and that of the external (spoken) language. He proposed that the internal language is of biological origin and underlies all human cognition—that it preceeds the external language but is not necessarily mirrored in it. Prof. Meltzer conculded by remarking that his conjectures were highly speculative and undeveloped, but nonetheless share an intuitive basis with other work in the field of linguistics which has led to similar theories.

Copies of the Proceedings of IJCAI6 may be ordered from:

IJCAI-79
Computer Science Dept.
Stanford University
Stanford, CA 94305

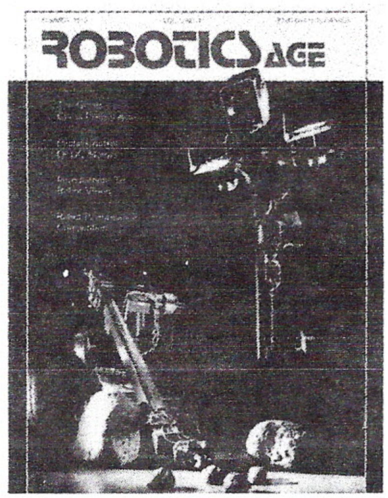
Enclose a check for US$25.00, payable to IJCAI-79, for book rate delivery. Add $5 for first class to the N. American continent, $20 air parcel post elsewhere. (Calif. residents add sales tax.) Proceedings of earlier IJCAI conferences are also available.

References (from IJCAI6 Proceedings)

[1] S. Tsugawa, et al, "An Automobile with Artificial Intelligence."
[2] T. Tsukiyama and Y. Shirai, "Detection of the Movements of Men for Autonomous Vehicles."
[3] T. Sato, "Automotive Stereo Vision Using Deconvolution Technique."
[4] E. Feigenbaum and J. Feldman, *Computers and Thought*, McGraw-Hill, NY (1973).
[5] J.-L. Lauriere, "Toward Efficiency Through Generality."
[6] H. Moravec, "Visual Mapping by a Robot Rover."
[7] T. Kurokawa, "LISP Activities in Japan."
[8] M. Nagao, et al., "NK3 and Measurement of its Performance."
[9] K. Taki, et al., "The Experimental LISP Machine."
[10] E. Goto, et al., "FLATS, A Machine for Numerical, Symbolic, and Associative Computing."

In his invited lecture, David Marr of MIT used Picasso's "Rites of Spring" to illustrate the point that we automatically infer three-dimensional shape from an image even when no depth information is present.

Sold Out!



Vol. 1, No. 1, Summer 1979

Due to the overwhelming demand for ROBOTICS AGE, the first printing of our Summer 1979 issue has quickly sold out. However, we are able to offer a limited number of copies for distribution. These are available in two categories:

- The *Collector's Edition*—The first 200 copies from the first press run have been individually numbered and signed by both the Editorial Director and the Publisher. These registered copies are available for $20.00, plus $1.50 for first-class postage and handling. (First issues of other popular magazines have often become worth hundreds of dollars.)

- Imperfect Issues—There are also a small number of issues which we held back due to various flaws such as loose pages, ink streaks, etc. These have been checked to ensure that the entire contents are complete and legible and may be ordered for $2.75 plus $1.00 for shipping and handling.

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ORGANIZATIONS

The American Association for Artificial Intelligence (AAAI)

The AAAI is a recently formed scientific society whose purpose is to further the dissemination of information on Artificial Intelligence research in the United States. The primary activities of the organization will be holding an annual AI conference, issuing a quarterly publication, and sponsoring related workshops and symposia. [*See below*] The AAAI will focus on new work in AI in the U.S. and, in affiliation with the Cognitive Science Society, will coordinate its meetings with other AI-related organizations such as IJCAI, ACM's SIGART, and the Cognitive Science Society.

The AAAI Organizing Committee, consisting of U.S. members of recent IJCAI Conference Committees, has elected Prof. Allen Newell of Carnegie-Mellon University as the first President, Prof. Edward Feigenbaum of Stanford University as President-elect, and Dr. Donald Walker of Stanfrod Research Institute as Secretary-Treasurer. All have generously agreed to serve in order to get the organization started. A general election, in which all full members can vote, will be held this winter.

The AAAI is open to all active researchers in Artificial Intelligence interested in developing the science of AI. Full-time students who have not yet been awarded a doctoral degree may join for one-half the regular membership dues of $10. Members of the public who are interested in AI may participate in the organization as nonvoting Associate Members, and will receive regular notices as well as a subscription to the quarterly publication.

The AAAI's official publication will feature discussions of issues related to current research, especially those that attempt to clarify and stimulate interest in unresolved problem areas. Also featured will be descriptions of work in progress and other news of interest to the AI research community.

Membership information can be obtained by writing to:
Prof. B. G. Buchanan, Chairman
AAAI Membership Committee
Computer Science Department
Stanford University
Stanford, California 94305 Circle 7

Calendar of Events

National Artificial Intelligence Conference, Sponsored by AAAI, August 19-21, 1980. Stanford University, Palo Alto, CA. Papers will be presented in a variety of topics in AI, including: Knowledge Representation, Problem Solving and Search, Natural Language, Program Synthesis, Vision, Robotics, Theorem Proving, Game Playing, and others. Information on the submission of conference papers may be obtained from the Program Chairman, Dr. Robert Balzer, USC/ISI, 4676 Admiralty Way, Marina Del Ray, CA 90201. Entry deadline is May 1, 1980.

1980 LISP Conference, August 24-27, 1980. Hosted by Stanford University Many areas of contemporary computer science have their spiritual roots in developments related to the LISP programming language. These include machine architecture, systems design, programming methodology and technology, and a theory of computation. Papers will be presented in several topics, such as: Languages and Theory, Programming Aspects, Architecture, and Applications. There will be several demonstrations, including new hardware LISP machines, and a panel discussion on the topic, "What is LISP?". Details for submitting papers can be obtained from Dr. John Allen, Stanford AI Lab, Stanford University, Stanford, CA 94305. Submission deadline is March 14, 1980.

United States Robotics Society
A Non-Profit Organization

"We thought maybe it would just quietly run down if we avoided publicity and slowly backed away."

So said Glen Norris, president of the United States Robotics Society, in announcing that, on the contrary, the three-year-old society is planning to expand to a full-fledged national organization. The self-described "quiet, little learned society" has generated so much interest that expansion has become inevitable.

Though specific details were not available at press time, Norris explained to ROBOTICS AGE the basic measures the society is undertaking:

- Support of ROBOTICS AGE and regular contributions to its pages.
- Establishment of a formal robotics collection. USRS is discussing such plans with a "small, aggressive university," whose library would house the collection. The collection would serve as a repository for incoming robotics information: books, reports, correspondence, films, tapes and other recorded media.

An immediate aim is remote computer access to the collection. The society is exploring the use of a low-cost commercial data network that would enable USRS members to address the collection index from terminals anywhere in the country. Whether keyboard inquiries will be possible depends on the society's success in gathering the required manpower, budget and time.

- Establishment of a communications office in California's Santa

(continued page 58)

NEW PRODUCTS

Visual Inspection from ORS

Object Recognition Systems Inc. is offering an inexpensive electronic system for recognizing complex objects or scenes in manufacturing environments. The ORS system works analogously to human visual recognition in that the system looks at an object through its input sensor (a closed-circuit TV camera, for example) and automatically makes a decision response based on what it has been "taught" to recognize.

The electronic signals from the input sensor are transmitted to the system's computer, where they are processed into a digital feature set uniquely representative of the object scanned. The computer then compares this set against other feature sets previously stored in memory that are representative of one or more objects or scenes. On a mathematical "closest-match" basis, the system makes an identification and initiates a decision response controlling an on-line activity—opening a gate to deflect a defective part and sounding an alarm are examples.

ORS system features include: real-time operation (the system can keep pace with almost any manufacturing process), recognition of scene differences that approximates human-eye performance, expandable memory capacity, problem independence, input-output versatility (inputs include CCTV cameras, charge-coupled devices, imaging-diode arrays; outputs include "go"/"no-go" triggers, computer interfaces, teletype or CRT displays). For more details, write or call: Object Recognition Systems Inc., 521 Fifth Ave., New York, N.Y. 10017 212/682-3535.

Circle 9

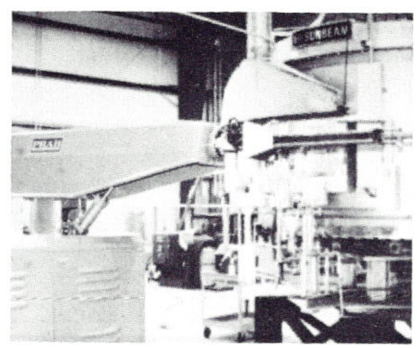
Software from Interface Technology

Interface Technology, specializing in microcomputers, is making available two new software packages. The first is the Z80-DES, a high-speed implementation of the National Bureau of Standards data-encryption standard with throughputs of more than 6,000 bps. Modular design permits flexible multi-user operation for data-base protection, password scrambling and telecommunications security. The package can provide secure links between home computers and remote data bases, and protection of sensitive or proprietary files.

Fully documented source code and documentation is provided, so the user can adapt the package to his own needs. A special version available for the TRS-80 allows protected files to be created on tape. Source and object files for the TRS-80 version are supplied. Versions for the Apple and Texas Instruments 990 are forthcoming.

The second is a floating-point arithmetic package for the TI 9900. The package consists of 14 routines, which perform such functions as floating addition, subtraction, multiplication and division; ASCII-floating-point conversion; negation; comparison; absolute value; and set precision. Among its features are selectable precision from four to 512 significant decimal digits, number magnitude range from 10^{-512} to 10^{508} and easy format conversion with no loss of accuracy. Fully documented source code will be available in January. Write Interface Technology, P. O. Box 745, College Park, MD 20740.

Circle 10



Robot Adds Solid State Programmable Memory

Prab Conveyors, Inc., Robot Division announces the availability of a solid state programmable controller designed to increase the capabilities of the entire Prab Robot

line.

The controller is taught right at the machine, which still utilizes the standard Prab Robot cabinet, and needs no more room than Prab's standard stepping drum control. With it, 48 functions can be controlled through 100 steps. In addition, random program selection is possible, with up to 4 distinct 100 step programs. With the controller in the teach mode one can enter the appropriate functions for each step, record that step and move to the next. One can also edit, erase and add additional functions or steps after the program has been completed. Light displays (LED) indicate the steps and the functions programmed and allow for easy diagnostics and troubleshooting of the program.

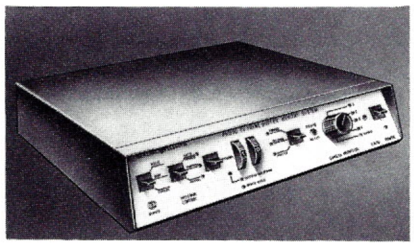
The controllers are capable of 50 inputs and 50 outputs and come with 8 timers as standard. A battery backup is provided to hold memory when the unit is temporarily shut off or in the case of power failure. The addition of the solid state controller allows full size Prab Robots to handle applications such as machine tool loading and material handling with greater number of steps, branch decision making and random program selection. Prab Conveyors, Inc., 5994 E. Kilgore Road, Kalamazoo, Michigan 49003 616/349-8761.

Circle 11

New Gearmotor For Robots

Gledhill Electronics is offering 12volt DC, 17-RPM, reversible gearmotors which produce 11 inchpounds of torque. Each motor requires 750-milliamperes full-load current. Two motors separately driving 6-inch diameter wheels will drive a 100-pound robot. The motors are $18.00 each, plus $1.50 per motor for shipping and handling, and 6% tax for California residents, from Gledhill Electronics, PO Box 1644, Marysville, California 95901.

Circle 12



New GE TV-frame Buffer Memory Device

General Electric Co. is marketing a new TV-frame buffer memory device, the PN2150, that adds full-frame memory capability to its solid-state Optomation Instrument System.

In conjunction with the TN2500 CID solid-state video camera, the new device may see numerous applications: in military and industrial surveillance; scientific instrumentation (astronomy, for example); slow-scan, narrow-band transmission; and data storage and processing.

The PN2150's memory can capture a given single frame of video information from a sequence of pictures being taken by the TN2500 camera and retain the information for later analysis, monitoring, data-rate conversion or narrow-bandwidth transmission. Recall is operator controlled or automatic.

The PN2150 can operate from one or more CID camera sources. Optional computer-personality modules allow interface to a number of standard computers via parallel or serial I/O ports. The versatile device permits simultaneous read/write operations with a continuous TV monitor display. In extremely low light, the PN2150 allows the CID camera to perform "black photography", that is, building an integrated image and storing in memory the elements of that picture.

Other features: 256 x 256 x 8-bit memory; manual, automatic or external control; 110/220 AC line voltage; rack mount desk console or rugged NEMA 12 enclosure.

For more details, write or call; General Electric Co., Optoelectronic Systems Operation, Building 3 Room 201, Electronics Park, Syracuse, N.Y. 13221. 315/456-2808, 456-2832.

Circle 13

Microcomputer System Features TV Input & Digital TV Display

The Beck-1/System combines a general purpose microcomputer system with a programmable display processor capable of digitizing a TV input signal and displaying a digital TV picture. The system is offered in a number of pre-packaged configurations spanning a broad range of price and performance. For volume OEM applications, the system can be custom configured.

Housed in a terminal-type enclosure, the unit inculdes a Z80 CPU, up to 64kb of CPU Ram and 32 kb of CPU Rom, serial and parallel I/O ports, floppy disc storage including both mini and standard floppy drives, a keyboard and CRT display. A DMA controller, real time clock and floating point arithmetic unit are also available.

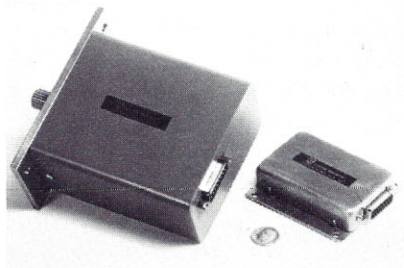
The Display Processor contains up to 32kb of image RAM which can be displayed as characters, graphics, or a digital TV (gray scale) picture. Programmable parameters include character and pixel size and count,

character blink, reverse, underline and half intensity. The unit features nondestructive zoom as well as horizontal and vertical panning in all 3 display modes. Pixel density of the TV input A/D and gray scale display is up to 256 x 240 bit (16 levels) pixels. Graphics densities are up to 512 x 480 1 bit pixels. The unit can supply a RS-170 compatible signal, interlaced or non-interlaced, or run off camera-supplied sync—RS170, RS330, or random interlace.

Applications utilizing the TV input and display capabilities include industrial non-contact measurment, surveillance, medical X-ray, ultrasound and CT displays, bacteria and cell analysis, broadcast effects, QC inspection, animation, robotics and many others in the rapidly expanding field combining TV and computer technologies.

Firmware provided includes the BECKMON-1 system monitor, containing basic console functions and disc bootstrap as well as I/O driver routines for all system devices, and BECKPLOT-1, containing I/O driver and plotting routines for the display processor, giving the user complete display control from high-level macro calls. The Beck-1 has software security features preventing the interchange of firmware or software between systems and a unique diagnostic capability whereby one Beck-1 can test another, without any disassembly.

The Beck-1/System is priced from \$3,400 for the Beck-1/30A, a basic system with no disc storage, to \$7,900 for the Beck-1/50C which includes TV in, graphics and digital TV display, 32kb CPU RAM, and dual standard floppy discs. Available from the Beck Corporation, 303 Slocum Ave., Neptune, NJ 07753 201/ 922-3579. Circle 14



Electromechanical Rotary Servo System

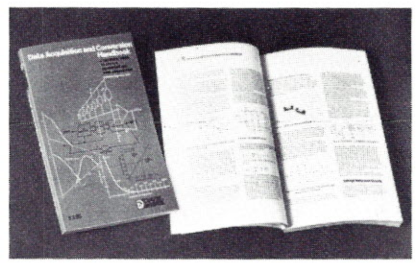
The new Model 7620 Rotary Actuators and Model 9620 Pulse Width Modulated Servo Amplifier form a closed-loop position servo to operate drones, RPV (Remotely Piloted Vehicles) and missile control surfaces.

The main features of this system are the samarium-cobalt permanent magnet DC motor, which produces a high torque/weight ratio; the Servo Amplifier as an integral design or at a remote location; high-impedance input actuator control signals of +10 VDC allow for direct interface to a microprocessor for servo control.

For further information, contact Russ Philipp, Marketing Product Manager, 215/622-1000 Ext. 396. Clifton Precision, Special Devices, Litton Systems, Inc., 5100 State Road, Drexel Hill, PA 19026 Circle 15

Interface Panel Simplifies Data Acquisition Wiring

Now there is no need to hand-solder and wire those connectors located on the back of rack mounted devices. Instead, the Datel Interface Panel brings these pins out to a front panel located on a rack mount in the form of 2 rows of 25 screw-on terminals. A user supplied plug located on the top left corner of the Interface Panel connects it to the user's device by ribbon cable. To increase reliability, this plug is hard-soldered by the user to a PC board which is in turn soldered to 2 rows of 25 screw-on terminals, providing a one-to-one correspondence between the pin numbers on the connector and those on the terminal strips. The unit measures 19" long (48.2cm) by 3.47" high (8.8cm) by 1/2" deep (1.27cm) and is supplied as two models: one with screening and the other without. Both cost \$195. Delivery is 4-8 weeks ARO from Datel Systems Inc., 11 Cabot Blvd., Mansfield, MA 02048, 617/828-8000. Circle 16

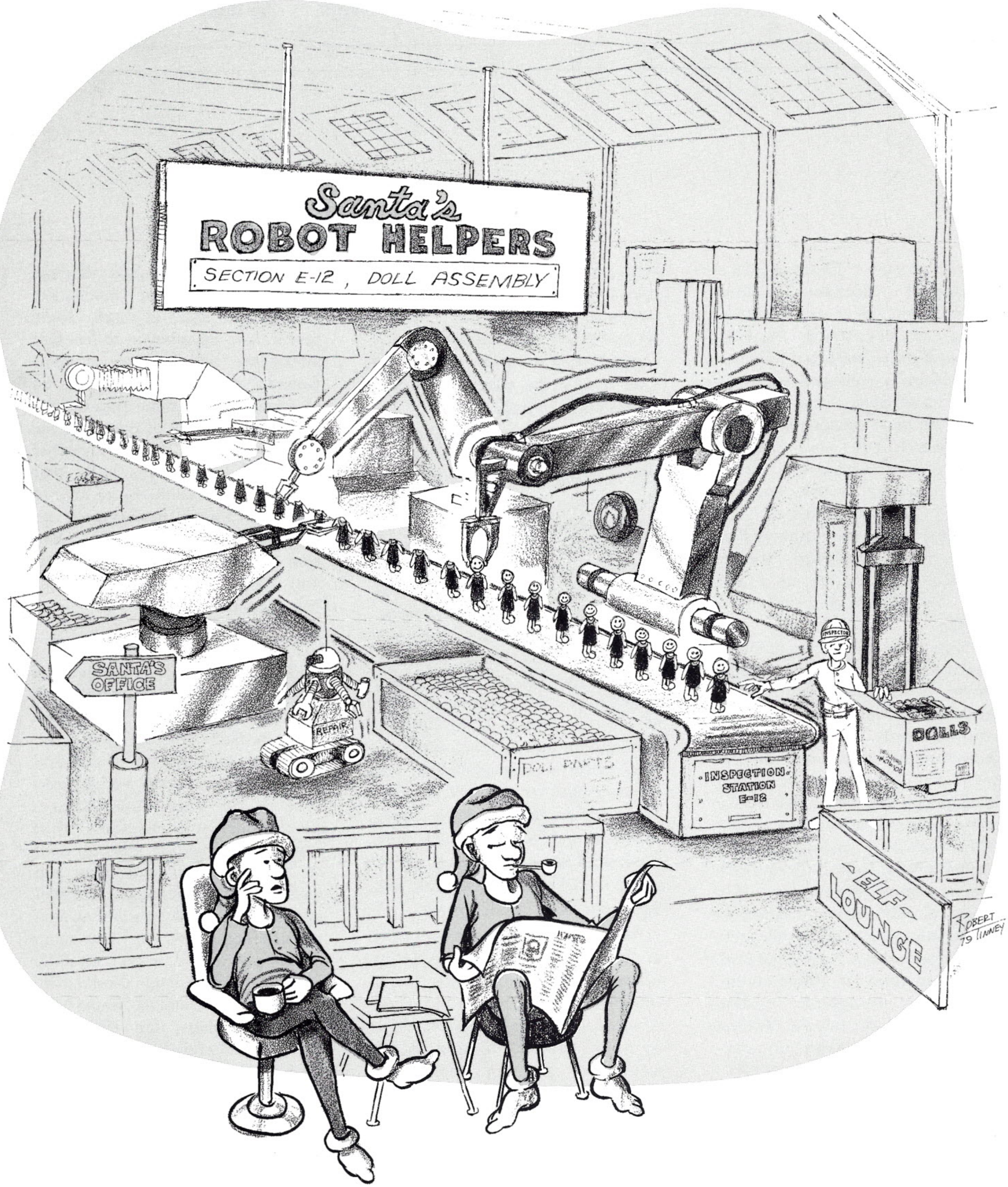


Data Acquisition and Conversion Handbook

Datel-Intersil Inc. has recently published a new handbook, *Principles of Data Acquisition and Conversion,* edited by Eugene L. Zuch, the company's manager of market planning.

The volume contains useful information on the theory and application of data-conversion circuits and systems. Topics inculde A/D and D/A converters, data-conversion systems, sample-holds, high-speed op amps and V/F converters. The handbook is in soft cover and measures 6 inches by 9 inches. Among its 242 pages are 35 technical articles, 312 illustrations, 40 tables and a glossary of 200 commonly used data-acquisition

(continued on page 58)



"FRANKLY, I DON'T KNOW HOW WE EVER GOT ALONG WITHOUT 'EM..."

MEDIA SENSORS

OMNI Magazine, October 1979—**"Intelligent Machines"** Smart machines are still a long way from seeing and scheming as the HAL computer did in *2001*, but they now exist and are beginning to change the lives of us all. Synthesized speech is one of the most successful areas of AI research. A new machine designed for the blind can scan a page, recognize words, and, by applying phonetic rules, it can determine where stress should be added and synthesize spoken sentences from the text as it goes along. The system is priced under $20,000.

Computers find understanding speech much harder. They must be trained to understand and it is still necessary to talk slowly with a pause between words. The next step is understanding continuous speech. Bell Labs has a system under development that will be able to take airline reservations over the phone. IBM's Yorktown Heights Research Center in New York is working on a voice-operated typewriter. Rex Dixon, of IBM, when pressed to predict how long it will be till voice-driven typewriters are perfected, expects to have "a usable continuous-speech recognition system working with all talkers, natural grammar, and large vocabularies in fifteen or twenty years."

Other AI systems demonstrate intelligent behavior in limited areas. Joe Weizenbaum of MIT has taught a computer to bluff its way through a conversation as a psychotherapist. Roger Shank of Yale is teaching "scripts" to computers, hoping to learn how our expectations may be used to draw implicit meaning from ambiguous statements. Other programs can scan a newspaper and summarize the major points and then update the summary as new details come in daily.

Computer vision systems are also under development. David Marr of MIT is trying to convert a digitized picture into a "primal sketch." This is closely related to the theory that the brain stores reference pictures of familiar scenes, greatly reducing the amount of data that must be processed to interpret a new image. Despite the problems, computer vision systems may someday surpass the eye's data-collecting ability. In the early 1960s researchers at Johns Hopkins University developed a mobile robot affectionately called the Hopkins Beast. The self-contained robot would continually search for electric outlets to plug itself into and "feed." SRI (Stanford Research Institute) built a robot that could read English commands and figure out ways to obey them.

Robot research today rests mostly in the hands of industry. Charles Rosen, SRI's former director of robotics research, thinks that most assembly jobs will eventually be done by robots. Robots will shorten the work week and shift people into service roles. Low-cost custom-made products will also be possible. Game playing has also become an important AI research area because scientists believe that games provide important models for studying human problem solving.

To date, AI research is not even close to producing human-like intelligence and in fact some researchers have begun to feel that intelligence and life are so intertwined that it may never be possible to produce a machine that is truly intelligent. In spite of this, Artificial Intelligence has almost unlimited potential, as it seems likely that machines will eventually be able to duplicate human performance on most everyday tasks. We have yet to face the social and psychological implications of the success of this new technology.

IN THESE TIMES, The Independent Socialist Newspaper, September 19-25, 1979—**"Tin Collar"** "New computerized technology undercuts work skills and job control and threatens to turn auto workers into robots." The United Auto Workers no longer acknowledges that management has the absolute right to introduce new machines and methods indiscriminately. The UAW points out that they are not against robots, computers or new technology *per se* and, in fact, strongly support increasing productivity through new technology. Rather, the article continues, the UAW demands are intended to give workers the means of preventing their power base from eroding due to the increasing use of "programmable automation." In the UAW's view all such systems should be under the control of blue-collar workers, even those systems which are leased or under warranty.

In another article titled **"The Brave New World of Work in Auto,"** Harley Shaiken accuses the auto companies of "replacing workers with robots" and of trying to "control workers as if they were robots." E. M. Estes, president of General Motors, is quoted as saying that "90 percent of the machines GM buys by 1987 will be computer-controlled." The old automation, observes Shaiken, was "hard" (inflexible) but this new automation is "soft" (programmable). The increased flexibility could be used either to improve the skills required of workers or to degrade them. Robots could be used to make employees work at an increased rate of speed. Robots could take over all the hazardous, monotonous and unhealthy jobs, or they could be given the good jobs at the expense of the workers.

Robots in factories today aren't like R2D2. They are stationary devices which can move car bodies, weld them, or load and unload or even assemble complex parts. Around 5,000 are in use world-wide and 2,000 in the U.S. Since the word *robot* causes people to fear the loss of their jobs, some companies call the machines "automatic transfer devices." As auto wages go up, the hourly cost of a robot stays fairly constant at around $4.80 per hour. Unless unions can gain a measure of control over the speed of their introduction, the use of robots may accelerate, making worker's wage increases harder to get.

The PUMA, which is said to have been developed by GM, is an example of a robot that is designed to take away the "good" jobs from workers, according to Shaiken. It does bench work like auto instrument panel assembly and can be used to replace operators in machine loading and unloading, or if the operators can't be eliminated, it can be used to set the pace of the work. GM is said to be thinking that robots and people can work on the same assembly line and this means that workers could be paced by machines on either side of them and forced to work at a rate determined by distant engineers and not the workers. GM engineers are quoted as saying that humans need to be retained in the system until vision and tactile sensors are perfected and become available at a reasonable price.

The real danger of the new soft automation is that it could destroy the unions' only real power, the power to strike, since it may become possible for a plant to operate without the workers. Managers and engineers surveyed by the Society of Manufacturing Engineers predict that by 1985, 20% of the assembly of a car will be done by robots and that by 1995 this will pass 50%.

Union official Pete Kelley, an alternate committeeman for the design staff at the GM Technical Center in Warren, Mich., said in an interview that he believes "we're on the verge of a new industrial revolution." He points out that a robot cost $28,000 and will work 24 hours a day, seven days a week with no breaks, whereas a human worker cost over $20,000 per year. He feels as though a worker may have to "... sit over in the corner and watch this machine for the rest of [his or her] life." Creativity should be used to open up new jobs and not to close them down, says Kelley.

Al Gardner of the tool and die unit at Ford's River Rouge Plant in the Detroit area feels that technology makes it possible to produce a better product at a lower cost but at the expense of jobs. However, a shorter work week or earlier retirement could take care of this problem. He sees the worst danger in the development of systems which don't increase productivity but rather "increase the control over the worker."

Editor's note: These stories were accompanied by drawings of ominous-looking robots like science fiction monsters, structured in such a way as to maximize what little scare value they were able to create in the text.

INDUSTRY WEEK, October 29, 1979—**News Analysis** Japan's success in boosting its productivity by 8% last year was partially accounted for by some 40,000 robots at work on Japanese production lines. An additional 10,000 robots were introduced last year alone by Japan's 100 robot manufacturers. Yukio Hasegawa of the System Science Institute of Waseda University says that although Japan is a world leader in robotics development, the technology is still "immature." However, he feels that "robot utilization has passed the trial stage, and a new era of wide use of robots has started." Dr. S. Inaba, president of Fujitsu Fanuc Ltd., said that the key to wider use of robots is to lower their cost in order to make it possible for smaller manufacturers to afford them. In the Nissan Motors factory there are 1,300 robots. An official indicated that the robots have reduced personnel requirements by 1,000 positions. On the average, one worker handles up to ten machines.

Media Sensors *are brief summaries of robotics-related items that have appeared in the mass media. An attempt is made to paraphase the content of the original item without altering its tone. The views expressed in these items are not necessarily those of ROBOTICS AGE. The first contributor of any clipping selected will receive $10 for its use.*

TECHNICAL ABSTRACTS

As part of our goal of disseminating current technical information to our readers, this department will list abstracts of significant recent technical papers, in cases where these papers are available to the public. The relevant addresses will normally be listed after the abstracts. We urge academic and industrial research centers to send us abstracts of recent papers in Robotics and Artificial Intelligence for possible inclusion in this department, with appropriate prices and ordering procedures.

Three Laws for Robotocists: An Approach to Overcoming Worker and Management Resistance to Industrial Robots, by Neale W. Clapp, SME MS79-775

Advances in industrial robot technology continue to exceed understanding of the dynamics of worker and management acceptance. Continued attention to developing equipment and applications with neglect or indifference to the "soft" science of management may result in sophistication without application, or installation "failure" wrongly attributed to technology, while the real problems of human interfaces remain unaddressed.

The crude basis for a beginning approach to confronting management and organizational issues may be the promulgation of "Three Laws of Industrial Robot Implementation." As a statement of management intention, they will be suspect. As a commitment to management action, they will prove themselves to both management and worker.

Furthermore, consistent with the laws, the robotocist would be well advised to explore innovative and social environmental benefits accruing from industrial robot application. Manufacturing management, currently "under siege," may, instead of resisting the inevitable, find reason for optimism in the demise of traditional patterns of work relationships.

Economic Analysis of Robot Applications, by John Behuniak, SME MS79-777

Economics is the principle justification for robot application in manufacturing operations. This paper reviews one approach to economics in robots. Screening criteria are outlined for use in critical plant surveys to identify potential robot applications. Design of installations using economic criteria and more detailed analysis for both appropriation requests and later review of completed projects is presented.

Robotics, by James H. Lockett, SME MS79-783

Robotics has opened up a new field in flexible automation by the introduction of an Industrial Robot Arm that has the ability to position and orient its wrist (commonly known as its End Effector) to any location within its designed three-dimensional range of operation. This paper describes a concept and program which is being conducted to develop a work station utilizing an Industrial Robot with specially designed "intelligent" tooling and compliance fixturing as a simple process to demonstrate the production of Aircraft Interchangeable and Replaceable Access Doors in small-batch production lots. The full scope of the paper includes a description of the overall development program with planned phases to program completion.

Use of Sensory Information for Improved Robot Learning, by Donald Seltzer, SME MS79-799

Robots "learn" or acquire knowledge by three different methods. Currently, the most popular method is through being "taught" by an operator during an on-line preparation phase. A second method is the use of off-line geometric data bases and software aids. A third, and as of now rarely used method is learning from on-line experience. The role of tactile sensory information in aiding learning is discussed for all three cases. A new type of tactile sensor developed in part for this purpose is described.

A Robot Task Using Visual Tracking, by Clifford C. Geschke, SME MS79-800

This paper describes the use of RSS, A Robot Servo System, for performing a visual tracking task. The task consists of inserting a bolt into a hole using dynamic visual feedback. The location of both the hole in the work area and the bolt in the robot gripper are determined visually in three dimensions, and the position of the bolt is updated an

average of ten times per second as the robot moves.

Included in the paper are discussions of the equipment and algorithms used to visually determine object location in three dimensions, the robot control scheme which allows the robot performance to degrade gracefully if the vision system fails, and a brief overview of the programming language. This task was successfully performed at the Coordinated Science Laboratory of the University of Illinois at Urbana-Champaign.

The Age of Robotics, by Gustave R. Gaschnig, SME MS79-874

The Age of Robotics is upon us. The 1978 SME Delphi Report states that by 1987, 15 percent of assembly systems will utilize robotics technology. General Motors is ready to start using the Programmable Universal Machine for Assembly (PUMA) in an integrated system for small component assembly. Vision as used with the ASEA robot is ready to come out of the laboratory. Tracking moving assembly lines is now a reality. Within a start time, the world will see the use of robotics being readied for use in many new markets. This presentation will review the state of the art as it exists today and a look into the future.

Ordering information for reprints of SME Technical Papers may be obtained from:
Society of Manufacturing Engineers
One SME Drive, PO Box 930,
Dearborn, Michigan 48128
Phone 313/271-1500

BOOKS

Artificial Intelligence, Patrick Henry Winston, Massachusetts Institute of Technology, (1977), Addison Wesley, 444 pages.

Written in 1977, Patrick Winston's *Artificial Intelligence* has quickly become quite popular as an introductory text for college level courses in Artificial Intelligence (AI). The book provides the reader with a good understanding of how the field has been defined through the 70s, presenting material in textbook form that heretofore was only available in journal articles, conference proceedings, or technical reports.

Artificial Intelligence is divided into two parts. The first discussing AI techniques in a non-programming way and the second discussing (and implementing) the different programming constructs required to "code" selected theoretical techniques. The text provides a step-by-step development of basic theories and ideas used in AI in a way that the novice as well as the experienced computer scientist can understand and use. Many illustrative AI examples are programmed for you.

The first part of text is designed to provide the reader with a theoretical basis for understanding what people in AI do for a living. Since AI is a comparatively young field there is still considerable debate as to what is and what is not AI. Winston does a good job in covering the breadth of the field, although the most detailed portions of the book stay close to the areas of his own theoretical interest. Specifically, there is not much discussion of heuristic search techniques (with the associated mathematical definitions defining their limitations) or of formal mathematical logic and its application to automatic theorem proving. There is, however, a good bibliography at the end of each chapter (as well as a summary of its salient points) to refer the interested reader to sources of related material.

Winston starts off with a general theme on how one would approach the study of intelligence. Using a standard "intelligence test" as an example problem, a general approach to its mechanical solution is presented. From that point he discusses the exploitation of constraints and how they can be used to narrow down an often horrendous number of alternative solutions to a few significant candidates to examine.

Next, Winston covers more basic AI issues. This part of the book might be classified as the "traditional AI" part of the text. The basic ideas of searching large sets of alternatives as well as basic principals of game theory are presented (mostly management techniques for large game trees). Discussed are the different techniques one may use to achieve a specified goal (either winning a game against an opponent or interpreting a line drawing of stacked toy building blocks.

In the next section a review of general problem solving technology is presented. Starting with GPS (an early AI system), then STRIPS (the problem solving system of the SRI "SHAKEY" robot) and finally to current "rule-based" systems, pros and cons of each architecture are discussed and related to the material discussed in earlier sections.

At this point a survey of natural language understanding is given. Leading off the chapter is Winograd's famous SHRDLU system, a simulated robot arm that moves blocks around on a table in response to natural language commands. Next, Augmented Transition Networks and finally Question/Answer systems are explained. Through discussing these techniques Winston shows that the understanding of natural language is a very complex and difficult task. (If you think about terms like "pick it up", "put it over there" or "give me the whatchamacallit, please" and how you might represent in a computer the context of the conversation so that you can easily resolve those references, you will see one of the problems inherent in automating language understanding.)

A whole chapter is devoted to the well-known "Frame" theory of Marvin Minsky and the types of intelligence that can be displayed using reasoning based on expectations.* Along with Minsky's theory, the structure of *semantic networks* (a technique for representing knowledge), *case grammars* (used to define the different interpretations that specific works can take) and *conceptual dependency* (a specific expectation-based knowledge representation scheme used to model human cognition) are discussed. In outlining these theories, Winston links back to the chapter on natural language understanding, as the utilization of expectations in constructing a context in which to select a meaningful interpretation is often very useful. (How would you interpret the sentence, "Time flies!"—As a remark on the swift passage of time or as a command to clock the speed of winged insects?

In the next chapter a broad overview of computer vision is given.

*See Robotics Age Summer 1979 for a discussion of the orginal paper, "A Framework for Representing Knowledge", by Marvin Minsky, included in Winston's *Psychology of Computer Vision.*

Drawing mostly from past work done at MIT, Winston outlines the field primarily utilizing idealized line drawings of toy blocks. He also discusses the early pattern recognition work done on blood cells, progresses through Shirai's line finder, continues with Marr's "primal sketch" approach to image understanding, and finishes with scene description techniques.

The production of expert programs that exhibit intelligence in real world domains is ultimately the physical realization of the theory presented in the book. The last chapter in the first half of the book is devoted to *Knowledge Engineering,* the techniques used to transfer expert problem solving behavior into a computer program. To illustrate, Winston presents several case studies. They are: DENDRAL (A program that analyzes mass spectrogram data produces interpretations that rival those of a highly trained chemist.); and finally the MIT Turtle (A small robot that is used to teach children universally useful ideas by having them program the robots to cope with differing environments.) This last section demonstrates that the field has indeed made contributions in automating intelligent activity in a domain-independent way.

The second half of the book is devoted to the programming aspects of the theories initially described. LISP as a language is discussed in detail, and its usefulness in AI systems is shown again and again by the ease with which Winston can generate examples of different AI constructions. Once a working knowledege of LISP is provided, the text continues by discussing and implementing the different program control structures that have become popular in many AI systems.

Going back to the SHRDLU example given earlier, Winston first discusses the different problems that Winograd encountered in the domains outside of processing natural language. Aspects such as representing the current world state, planning, hypothetical reasoning, and question-answering are all discussed, and programs are given which give you a feel for how these functions are accomplished. Winston next enters the world of games. Earlier, game theory was discussed in detail and in this section the implementations of both *minimax* and *alpha/beta* pruning methods for managing game trees are given.

Pattern-matching is the next area of discussion. By using the DOCTOR program (a program that mimics the behavior of a psychiatrist) and STUDENT a program that solves algebra word problems), the utility of a LISP program containing domain knowledge and a pattern matcher is shown. In the case of the DOCTOR program, people not familiar with its structure deemed it quite intelligent—although all it did was match predefined templates against input supplied by the human users.

The last section in the second half of the book discusses databases and *demons.* Building on the earlier pattern matching discussion, Winston describes how to implement a database mechanism in LISP consisting of functions that fetch, add and delete items from the database, as well as a facility to react to specific additions and deletions (the structure that implements this ability is called a *demon).* In the latter part of the chapter, an entire system is presented which reasons about actions performed in a computer model of the Garden of Eden.

In conclusion, I consider *Artificial Intelligence* to be one of the best introductory texts on the field. It uses a very intuitive approach to get its ideas across and provides the reader with real live programming examples of theory. The division of the book into programming and non-programming contexts is extremely useful and, as I stated earlier, increases the appeal of the book much beyond a traditional computer science realm. I heartily recommend this book to people who are seriously interested in finding out just what people who make computers intelligent do for a living.

—Mache Creeger

Mache Creeger is with the NASA/JPL Robotics Research Program.

terms. The book is available by mail for $3.95 (in Massachusetts add 5% sales tax; outside U.S. and Canada add $2.75 for handling and air mail). Write: Datel-Intersil Inc., Marketing Department, 11 Cabot Blvd., Mansfield, Mass. 02048 Circle 17

Analog to Digital Conversion System for the Pet/Kim Computers

The PETSET1 gives the Commodore Pet computer 16 channels of analog input, each with a resolution of eight bits. This system lets the Pet computer read temperature, light levels, etc. under program control. The PETMOD plugs into the Pet at the IEEE and USER ports and provides the user with two IEEE ports, one USER port and a DAM Systems port. The Cable A24 connects the PETMOD to the AIM161.

The AIM161 is addressed by the user's program to convert one of the user's sixteen analog inputs (0 to 5.12 volts) to its equivalent decimal value (0 to 255). The MANMOD1 plugs into the AIM161 and provides screw terminals for the ground, reference and analog inputs.

For the KIM computer, the KIMMOD is used to interface to the AIM161 with cable A24. The KIMMOD plugs into the KIM at the applications port, providing the user with another applications port as well as the DAM Systems port.

The PETSET1a includes the PETMOD, Cable A24, AIM161, MANMOD1, POW1 power supply, instructions and software and sells for $295.00 plus shipping. The PETSET1e, with a 230V power supply, sells for $305.00 plus shipping.

The KIMSET1a includes the KIMMOD, Cable A24, AM161, MANMOD1, POW1 power supply, instructions and software and sells for $285.00 plus shipping. Availability is from stock from DAM Systems, 150 Pocono Rd, Brookfield, Conn 06804 201/775-9659. Circle 19

New Products Policy

ROBOTICS AGE encourages the manufacturers of products related to robotics and automatic control applications to send in New Product announcements for this department. Readers are advised that, although ROBOTICS AGE selects new products for publication based on our estimation of their relatedness to the field, in most cases we have not evaluated either the product or the company and, although we would not knowingly print any inaccurate information, no endorsement of any product is implied. Send announcements of New Products literature to ROBOTICS AGE, New Products, P. O. Box 801, La Canada, CA 91011.

ORGANIZATIONS

(continued from page 47)

Clara ("Silicon") Valley. There, a staff would handle correspondence, generate newsletters and bulletins, and search actively for information and contacts of value to society members.

- Expansion and update of the USRS discount book lists. The society hopes to add appropriate discount purchases to the lists, which have been very popular with USRS members.

These measures come despite the initial reluctance of USRS directors to create a large organization, borrow money and plunge into what they call the "inevitable" politics of a growing field. They feel that growth involves more exposure to such pressures and thus a need for professional discipline and economic staying power.

But now, apparently, the people and the capital are available to match the widespread interest the society has generated. And, the society reports, "a fresh new wave of international correspondence adds to the conviction that USRS is dealing with something real and important in our society." Thus the expanded organization will continue as an independent, noncommercial, impartial body that can collect and distribute information on robotics, and provide meeting places, some structure for events and an interested ear for people who have something to say about robotics.

For more details, write: United States Robotics Society, P.O. Box 26484, Albuquerque, NM 87125.

Circle 8

LETTERS

(continued from page 5)

you correctly pointed out in your letter, the experience gained from designing and building a tele-operated robot will be immensely valuable for the development of future practical robots. Most of the hardware requirements are identical—it is the development of effective computer algorithms for automatic control that characterizes the difference between teleops and autonomous robots.

For this latter reason, it would be difficult to structure a teleoperated robot category for the RACE contest (described in our first issue). Modern man-machine systems have grown so complex that the fields are really divergent in many respects. If the category was limited to "show robots," the question of judging is highly subjective (except possibly using an applause meter!). For these reasons we decided to avoid having categories for hardware alone, especially given that hardware performance is, to a large extent, directly proportional to dollars invested, and concentrate on computer-controlled equipment. Control algorithm development is an area in which everyone can compete almost without regard to investment. Even so, the issue of how to bias the contest in favor of low-cost robots is still problematical.

As we pointed out elsewhere in the first issue, we encourage all forms of robot development. Experimenters can get a lot of experience and satisfaction from building teleops, and computer control can be added later at any time to expand into what we consider the most challenging area—on-board sensory processing and autonomous behavior.

—AMT

Dear Editor:

I am developing a unit on robotics for gifted 7th and 8th graders. The research has led me down many wonderous paths so far. I, in turn, will entice the youngsters with references to everything from artificial intelligence to algorithms, and see where *they* lead me in their pursuit!

With robots on the brain, I wandered into a magazine today looking for an issue of something else, when lo and behold, there was your magazine! I am ordering a subscription for the school library out of next year's budget. These students will be hungry for your news.

So, congratulations on a fine first issue. We will look for the next. By the third (Spring, 1980), expect to hear from us, for, if all goes well, these aspiring roboticists will be well on their way to completing a robot of their own design. I'm sure they would want to submit an article to you.

Keep up the good work.

Abby Gelles
Educational Consultant
Gifted Education Tech. Consultants
Personal Computing Society, Inc.
New York, NY 10014

Dear Abby,

Thanks for the compliments—we look forward to hearing from the many school and home experimenters we know are out there. It is important to realize that a university education is by no means a prerequisite for creating better robot hardware and program designs—although it helps a great deal. We want to help provide that background and the motivation that such innovation requires.

—AMT

apple computer

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Apple II Monitor Peeled	9.95
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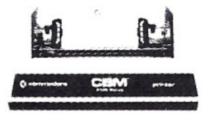

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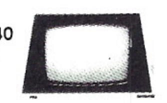

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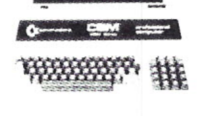

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